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Hydrogen sulfide spatial distribution and exposure in deep-pit swine housing

by

Randy John Swestka

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Agricultural Engineering

Program of Study Committee:
Robert T. Burns, Major Professor
Steven Hoff
Nir Keren
Hongwei Xin

Iowa State University

Ames, Iowa

2010

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ACKNOWLEDGEMENTS

I am deeply grateful to Dr. Robert Burns for the opportunity to research hydrogen sulfide gas in deep-pit swine housing systems. It was a privilege to educate the public of hydrogen sulfide in extension programs. I am especially thankful for the opportunity to be involved in many other research projects. It has been an honor to learn from and work with the best. I would like to thank my committee members: Dr. Steven Hoff, Dr. Hongwei Xin, and Dr. Nir Keren for their valuable advice and guidance in my research and education. Most importantly, their encouragement motivated me to succeed.

I would like to thank Dr. Lun Tong, Dr. Hong Li, and Dr. Matthew Darr for their assistance with instrumentation and data acquisition systems. Lara Moody and Ember Muhlbauer for reviewing and providing insight on almost every document I put in front of them. To Ross Muhlbauer, it was his vision of hydrogen sulfide detection which launched this research, for his encouragement and guidance I am most grateful.

I owe a great deal of gratitude to the long list of members of the Agricultural Waste Management Group. It has been a privilege to work with you all.

Last but not least, I’d like to thank my family and friends for their incredible support and encouragement in all aspects of my life.

CHAPTER 1. GENERAL INTRODUCTION

Introduction

Hydrogen sulfide gas (H_2S) has been identified as a health hazard to humans and swine in deep-pit production systems (Donham et al., 1982; Donham and Gustafson, 1982). Hydrogen sulfide is formed under anaerobic conditions by bacteria reducing sulfate to form sulfide. This sulfide then combines with hydrogen ions to form H_2S. Acute exposure to high concentrations of hydrogen sulfide is potentially lethal during manure agitation and removal events in deep-pit swine housing. While slurry applicators and producers note that swine loss tends to occur in corners of barns or near agitation activity, the spatial distribution of H_2S has yet to be described during slurry removal events in deep-pit swine barns. Literature indicates a need for hydrogen sulfide spatial distribution data from near-simultaneous measurement.

In deep-pit swine housing systems, commonly used in the Midwestern U.S., the animals are housed on slatted floors above the manure storage area. Throughout the production cycle, human caretakers frequently enter the swine barn. However, it has been widely recommended that no one enter a barn due to H_2S releases from the manure slurry during agitation events. Lethal hydrogen sulfide concentrations have been documented in the animal growing area during swine manure slurry agitation in deep-pit facilities (Patni and Clarke, 2003; Muhlbauer et al., 2008). However, entries still occur sometimes resulting in human death.

Agitation of the manure slurry within deep-pits is common to create a homogeneous product for land application. Swine manure slurry is commonly land applied as fertilizer for crop production. One common design for slurry removal pumps is a vertical shaft drive pump. This pump transfers the rotation of a tractor PTO down a shaft to an impeller. When inserted into a deep-pit, the impeller is located near the bottom of the pit. A nozzle above the impeller is used to recirculate slurry, thus mixing the manure slurry within the pit.

Objectives

The objectives of this research focus on investigating spatial distribution of hydrogen sulfide gas associated with manure removal and agitation events in deep-pit swine production facilities as well as assessing exposure or potential exposure to hydrogen sulfide before, during, and after manure removal and agitation events. The specific objectives of this study were:

1. Implement a wireless H_2S monitoring network in deep-pit sow and finishing swine facilities.
2. Measure the in-house distribution of H_2S concentrations in deep-pit sow and finishing swine facilities before, during, and after pit agitation and pumping events.
3. Compare measured H_2S concentrations to OSHA exposure guidelines (during normal operation) and animal exposure levels (during normal and pit agitation and slurry removal) for different swine facility types.
4. Develop management options that reduce worker and animal exposure risks to H_2S in swine production facilities.

Thesis Organization

The research presented in this thesis is comprised of three papers, each corresponding to specific research objectives. The first paper entitled “A Wireless Sensor Network to Quantify Hydrogen Sulfide Concentrations in Swine Housing” will be submitted to *Applied Engineering in Agriculture* for publication. The second paper entitled “Spatial Distribution of Hydrogen Sulfide in Deep-Pit Swine Housing Associated with Slurry Removal Events” will be submitted to *Transactions of the ASABE* for publication. The third paper, “Assessment of Hydrogen Sulfide Exposure in Deep-Pit Swine Housing” will be submitted to the *Journal of Agricultural Safety and Health* for publication.

Literature Review

Hydrogen sulfide is formed by bacterial sulfate reduction and the decomposition of organic compounds containing sulfur to sulfide in manure under anaerobic conditions. The sulfide then combines with hydrogen ions to form hydrogen sulfide. Different sulfides exist in an aqueous solution at a range of pH values, as shown in figure 1.1. In solutions with a pH of 7, H_2S and HS^- are present in equal concentrations. As pH decreases, more hydrogen ions are available and thus more hydrogen sulfide is present. Below a pH of 5, all sulfides in solution are hydrogen sulfide (Snoeyink and Jenkins, 1980).

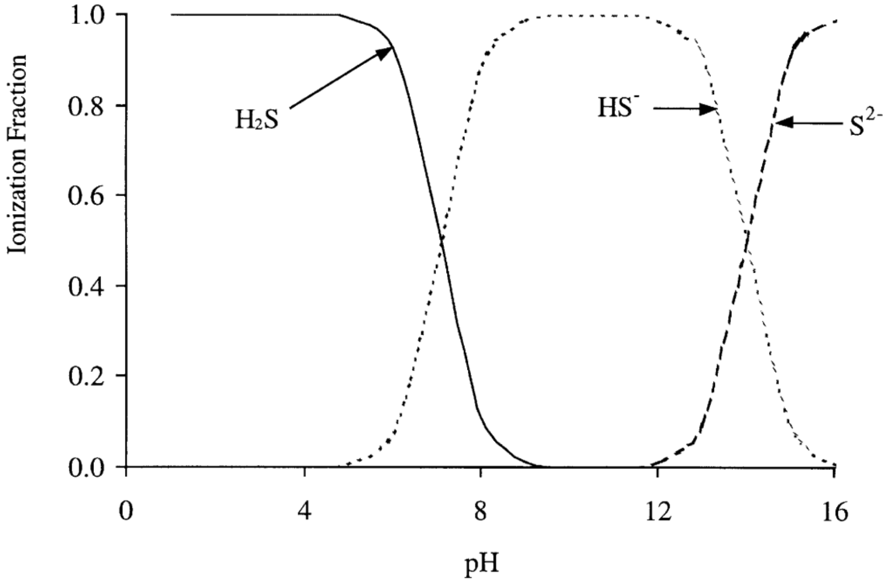

Figure 1.1. Fractions of sulfides present in solution at 25° C as a function of pH (Snoeyink and Jenkins, 1980).

In a swine deep-pit, sulfates can come from water used for drinking or washing the barn. Other sulfates can come from feed waste or swine manure. Hydrogen sulfide production in swine confinements has shown a significant correlation to the daily sulfur intake of the housed swine (Avery et al., 1975). If the manure in a swine deep-pit is not aerated, the manure undergoes anaerobic decomposition. Zhang and Day (1996) simulated a swine deep-pit and determined pH decreases toward the bottom of the pit. This is where organic matter is most concentrated and anaerobic conditions exist. The lower pH indicates the presence of more hydrogen ions which can combine with sulfide to form hydrogen sulfide. A laboratory study by Arogo et al. (2000) simulated a deep-pit swine manure storage by allowing manure of differing total solids to settle for 24 hours. It was determined the top layer had the lowest total solids content and the highest total sulfide concentration in all cases. However, due to more available hydrogen ions in the bottom layer compared to the top layer, the bottom layer contained more hydrogen sulfide.

Measuring Hydrogen Sulfide Gas

Multiple methods have been used to measure hydrogen sulfide gas in livestock facilities. Patni and Clarke (2003) and Zhao et al. (2005) used diffusion-type detector tubes to measure hydrogen sulfide concentrations in swine barns with sub-floor pits. In these studies, pumps were required to provide air to the detector tubes. Furthermore, detector tubes are a grab sample technique resulting in a single concentration for a representative time period. Highly accurate, expensive lab grade analyzers have been used to measure hydrogen sulfide concentrations during livestock emissions studies, as shown in table 1.1. This technology requires pumps and tubing to collect air from the desired sample location (Li et al., 2008; Moody et al., 2008; Hoff et al., 2006; Ni et al., 2002). During slurry agitation however, short duration bursts could be concealed due to the time interval and stabilization period associated with sampling multiple locations utilizing a mobile lab (Ni et al., 2000).

Table 1.1. Monitoring equipment and measurement range used by previous researchers measuring hydrogen sulfide in livestock environments

Reference	Monitoring Equipment	Measurement Range
Li et al, 2008	API Model 101E	1-20 ppm
Moody et al, 2008	API Model 101E	1-20 ppm
Hoff et al, 2006	TEI Model 45C	0-50 ppm
Ni et al, 2002	TEI Model 340 and 45C	1-10 ppm
Liang et al, 2004	TEI Model 450TCL	0-0.1 ppm
Zhao et al, 2005	Jerome H_2S Analyzer Model 631X	0-50 ppm

Other research studies have utilized commercially available passive sensors which do not require a pump and tubing to collect air samples (table 1.2). Passive sensors measure the gas concentration in the ambient air which comes in contact with the sensor head. This type of sensor is typically used as personal monitoring devices for workers or as ambient air monitors in industrial facilities. Patni and Clarke (2003), Chénard et al. (2003), and Muhlbauer et al. (2008) verified sensor performance with certified H_2S calibration gases. Muhlbauer et al. (2008) tested the Pem-Tech PT295 H_2S sensor during slurry agitation events in a deep-pit swine confinement and found the sensor was within five percent full-scale accuracy (±25 ppm) of a pulsed fluorescence lab analyzer during rapidly changing concentrations. During steady state conditions the sensor was within ±5% reading error of a pulsed fluorescence analyzer. (Model 45C, Thermo Environment Instruments).

Table 1.2. Monitoring equipment and measurement range used by previous researchers measuring hydrogen sulfide in livestock environments using commercially available electrochemical sensors

Reference	Monitoring Equipment	Measurement Range
Patni and Clarke, 2003	Compur-Electronic GmbH	1-100 ppm
Patni and Clarke, 2003	Drager	1-200 ppm
Chenard et al, 2003	Drager Pac III and XS EC	1-1,000 ppm
Muhlbauer et al, 2008	Pem-Tech PT 295	1-500 ppm

Wireless Sensor Networks

Wireless sensors networks have increased in scientific use in recent years as cost has decreased and functionality has increased. Wireless communication is not restricted to the physical constraints associated with wired communication.

Furthermore, wireless communication provides dynamic mobility and cost-free relocation of sensing elements. Simple point-to-point sensor networks were the start of wireless sensor networks and have demonstrated success in agricultural applications.

Muhlbauer et al. (2008) paired a point-to-point wireless data transfer system (Phoenix Contact I/O radio) with a hydrogen sulfide sensor to develop a wireless hydrogen sulfide detection system. A single sensor transmitted data to a single receiver to display the current hydrogen sulfide concentration at the sensor location. The system provided information previously unavailable to swine workers and slurry applicators.

Bluetooth technology has been used to automate variable-rate irrigation based upon soil and environmental conditions (Kim et al., 2006). Reliable connectivity was maintained to 700 m across a crop field. The component cost for each plug-and-play Bluetooth wireless module was $1,072. Bluetooth technology is more common between complex devices such as computers, cellular phones, and printers. Operation complexity and power consumption tend to be directly related. The more operations or procedures a device completes the more power the device requires.

Wireless mesh networks have increased in use in agricultural environments in recent years. The Zigbee communication standard was recently developed for low power consumption, data rates less than 250 kb/s, and low-cost applications (IEEE, 2003). In comparison to WiFi intended to transmit large files like images or audio, Zigbee is intended to transmit small amounts of data such as sensor readings or control signals. In a wireless mesh network operating in the Zigbee standard, each node can act as a router or repeater to forward data to the next node within its transmission range. Ultimately, this progression of forwarding messages will land the message at its final destination. However, as more hops are required bandwidth is consumed thus reducing the throughput capacity of the network. Zigbee networks employ automatic discovery of nodes into the network. Thus, upon start-up the network is formed according to defined parameters within each module. All nodes acquire addresses of other nodes within transmission distance and the nearest data sink. Any nodes losing connectivity will go through this discovery process automatically once discovering another node within its defined operating channel.

Hebel (2006) explored the requirements and considerations for employing Zigbee wireless network technology in agricultural applications. Transmission signal strength is governed by the power transmitter level and the amount of obstructions in a football shaped area between a transmitter and receiver called the Fresnel Zone (Hebel, 2006). Thus, for use in crop environments special consideration needs to be given to the height of the crop. Zigbee nodes can be programmed to cycle between a low-power state or “sleep” when not transmitting data and an active state to transmit data. One opportunity is monitoring micro-climates within a vineyard to ensure grapes are harvested at optimal times. The use of Zigbee technology has been demonstrated successful in agricultural applications.

Temperature variation within swine barns was monitored with Zigbee wireless network technology (Darr and Zhao, 2008). Transmission distances up to 250 m were possible with twenty-eight wireless temperature nodes inside a 1,000 head swine finishing barn. Each data message was provided in a simple string format with an identifier for the transmitting node, a transmission counter, and status of digital I/O and analog-to-digital conversion registers. A sleep mode was incorporated into the operation of the wireless temperature nodes to conserve power when not transmitting data. On a timed interval the node would “wake up” transmit a message and return to the low-power sleep mode. Battery life was estimated to be approximately 550 days with a 1,000 mA-hr battery. The total component cost for each wireless temperature sensing node was $72.

Spatial Distribution of Hydrogen Sulfide in Swine Barns

Limited literature exists that investigates the spatial distribution of hydrogen sulfide in swine barns. Some literature comments on spatial characteristics but does not report spatial data or statistical analysis. Research by Zhao et al. (2005), in two swine barns (one deep-pit and one shallow-pit pull-plug), described hydrogen sulfide spatial distribution during normal operation conditions. As shown in figure 1.2, hydrogen sulfide was monitored at human head height in the center alley and pig head height in the pig pens. Hydrogen sulfide concentrations were between 100-200 ppb in the first 50 m from the inlet end in the deep-pit barn for all three monitoring events and through the entire length of the barn in the shallow-pit pull-plug barn during two events. In the 11 m nearest the exhaust fans in the deep-pit barn, H_2S concentrations rose to 450, 350, and 1,000 ppb during event 1, 2, and 3, respectively. The H_2S concentration increase at the exhaust end of the barn was believed to be because there was more volume of pit gases pulled into the end wall fans. However, the results do not represent instantaneous distribution because the data were collected over a 2-3 hour period. A major conclusion of this research was that more equipment is needed to record spatial distribution with respect to time.

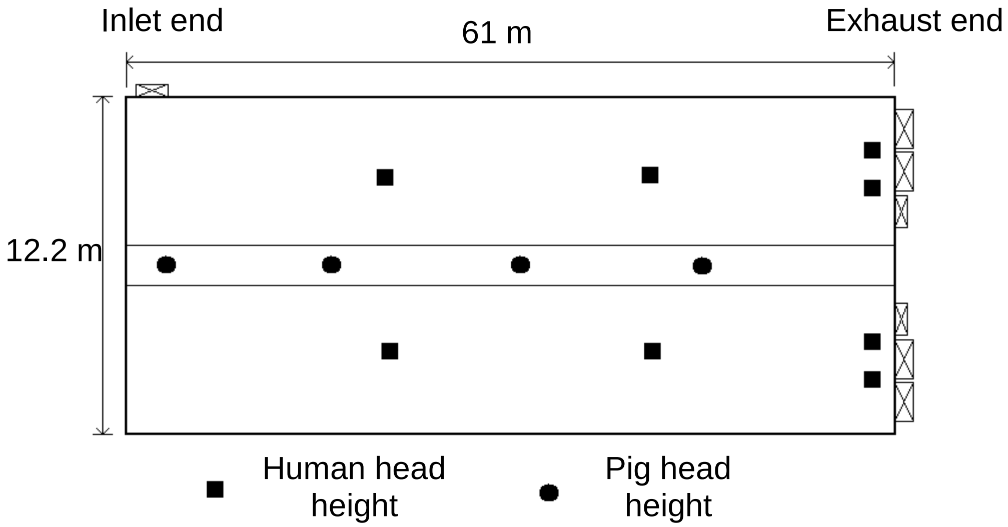

Figure 1.2. Monitoring locations of Zhao et al. (2005) gaseous spatial distribution inside deep-pit wean-finish swine barn. Adapted from Zhao et al. (2005).

In a shallow-pit (0.45 m depth) swine barn, hydrogen sulfide concentrations were significantly different between the pig breathing zone (0.3 m above the floor) and the human breathing zone (1.5 m above the floor). Kim et al. (2007) reported the average of three measurements for this eight hour experiment was 55.29 ppb and 42.23 ppb H_2S in the pig and human breathing zones, respectively. Since hydrogen sulfide is denser than air it is likely concentrations would increase as the distance above the manure surface decreases.

Chénard et al. (2003) reported the plug area where manure is drained from a shallow-pit is most often the location of the peak hydrogen sulfide concentration during plug-pulling events. However, there was no observable trend to characterize the location when peaks occurred in other areas of the barn. The maximum hydrogen sulfide concentrations recorded during plug-pulling events was 810, 1,000, 494, and 1,000 ppm for farrow, gestation, grow-finish, and nursery barns, respectively. The maximum detection limit of the monitoring equipment was 1,000 ppm. The concentration in these events could have been greater than 1,000 ppm.

Ten deep-pit barns in southern Ontario were monitored for hydrogen sulfide during slurry mixing events (Patni and Clarke, 2003). Concentrations were measured at floor level and 0.9 m above the floor using electrochemical sensors and detector tubes. Results showed localized high H_2S levels corresponded to the location of manure splashing in the pit during recirculation agitation. Furthermore, increased slurry turbulence and splashing of the slurry within the pit increased the concentration and the rate of release of H_2S compared to agitation below the slurry surface. The highest concentrations (1,000 and 1,300 ppm) were observed at the slat floor when slurry was mixed by blowing air from vacuum tankers into the slurry. However, no statistical analysis was reported to determine differences among sensor locations. Furthermore, the report does not describe the monitoring locations among the horizontal axis of the barns, nor the total number of locations monitored within the barns.

Muhlbauer et al. (2008) monitored hydrogen sulfide in two locations within a deep-pit swine barn during multiple slurry agitation events. In one test, hydrogen sulfide concentrations 0.51 m below the slat floor in the pit headspace were 10-30 ppm less than above the slat floor during above surface agitation. Three minutes after stir fans were activated the concentrations at both locations were within 1 ppm. This suggests stir-fans can be used to create a uniform hydrogen sulfide profile within a deep-pit swine barn. However no statistical analysis was performed to determine if there was a significant difference above and below the slats.

Hoff et al. (2006) monitored hydrogen sulfide emissions from two swine deep-pit finishing facilities during slurry removal and agitation events in 2002 and 2003. The peak hydrogen sulfide concentrations recorded before, during, and after the slurry removal event in 2002 were 1,775 ppb, 15,918 ppb, and 197 ppb at the sidewall fan, tunnel exhaust fans, and sidewall fan, respectively. The peak hydrogen sulfide concentration recorded before, during and after the slurry removal event in 2003 were 678 ppb, 35,825 ppb, and 678 ppb at the sidewall fan, pit exhaust fans, and sidewall fan, respectively. There are no statistical comparisons of the monitored locations. This suggests for periods outside slurry removal the highest concentration H_2S is above the slats on the end of the barn opposite the tunnel exhaust fans.

Hydrogen Sulfide Exposure

The American Conference of Governmental Industrial Hygienists (ACGIH) and National Institute for Occupational Safety and Health (NIOSH) devise recommendations or threshold limit values (TLV) for safe exposure to hazards, as shown in table 1.3. These exposure guidelines have been adopted by the United States Occupational Safety and Health Administration (OSHA) as regulations for exposure. However, agricultural operations are not governed by OSHA’s limits for air contaminants based on 29 CFR 1921(b) of the Federal Register.

Table 1.3. Guidelines for exposure to hydrogen sulfide.

	TLV-TWA	**TLV-STEL**	**TLV-CEIL**	**IDLH**
Concentration, ppm	10	15	20	100
Concentration, mg/m^3	14	21	28	140

A worker should not have adverse health effects when exposed to a concentration equal to or lower than the specified time weighted average, TLV-TWA. The TLV-TWA assumes a worker exposure of eight hours per day for a maximum of 40 hours per week. For exposures over the TLV-TWA, the short term exposure limit (TLV-STEL) is a concentration to which workers may be exposed to for a period of 15 minutes only. Each exposure must be separated by at least one hour and not occur more than four times a day. The concentration which should not be exceeded regardless of exposure duration is called the ceiling concentration (TLV-CEIL). NIOSH developed the immediately dangerous to life or health (IDLH) guideline. This is a concentration that is likely to prevent escape from the environment or cause permanent negative health effects. The lethal concentration to 50% of the population (LC_{50}) is based on toxicity testing on animals, usually rats. The hydrogen sulfide LC_{50} found on many material safety data sheets is 444 ppm.

Published reports indicate that hydrogen sulfide poisoning was responsible for the death of 24 swine workers in the Midwest from 1983 to 1990, and at least 15 more deaths since 1994 (Wallinga, 2004). Hydrogen sulfide poisoning also occurs in swine. Puck Custom Enterprises (PCE) is a custom manure removal and application business located in western Iowa. In the past PCE has experienced an average of 20-30 swine per year succumbed to H_2S poisoning associated with slurry agitation in deep-pit swine production systems. Puck Custom Enterprises reports when swine loss is localized to an area away from the agitation source, insufficient ventilation or unfavorable airflow patterns allowing H_2S to accumulate is suspected to be the cause. Puck Custom Enterprises also reports swine loss localized to the agitation source. The worst event for PCE occurred in January of 2006 when 300 market-size swine died from H_2S poisoning in a single barn (Puck, 2008).

Donham and Popendorf (1985) conducted an assessment of 21 Iowa swine confinements during normal operation conditions. In this study hydrogen sulfide was detected in eight of the 21 confinements (five farrowing barns, two nursery barns, and one finishing barn). The mean concentration of the eight barns where hydrogen sulfide was detected was 1.4 ppm. The concentration was below the ACGIH exposure guideline of 10 ppm, and it was determined hydrogen sulfide was not an acute health hazard during normal operation conditions.

Donham et al. (1982) conducted a series of case studies on six accidents with humans and liquid manure storages. In four of the six accidents at least one person died due to hydrogen sulfide poisoning. Of those four accidents, three were during manure slurry agitation in a storage pit. In the other two accidents, humans suffered loss of breath, nausea, and in some instances unconsciousness. These symptoms are representative of acute exposure to high concentration hydrogen sulfide. One accident reported all swine (24 sows and 200 piglets) died in the end of the building where manure was being agitated. During an attempt to recreate one of the accidents, hydrogen sulfide levels quickly rose from 0 ppm to greater than 400 ppm as the liquid manure was agitated.

Experiments on hydrogen sulfide poisoning in swine can be found dating back to 1961 (O'Donoghue). In a controlled environment 30-35 lb swine were exposed to varying amounts of hydrogen sulfide for different durations. Animal distress was characteristic at 250 ppm H_2S. Above 400 ppm swine became unconscious and in multiple instances death occurred. One instantaneous exposure to 400 ppm H_2S caused immediate death. It was concluded that toxicity was related to the concentration of H_2S rather than the duration of exposure. No chronic effects were observed in the swine surviving exposure to H_2S. This indicates if immediate action is taken to mitigate poisonous H_2S, swine can recover with no lasting health effects.

The American Society of Agricultural and Biological Engineers manure storage safety standard no. EP470.8 contains technical information on manure gases. Specifically EP470.8.1 discusses the symptoms swine (table 1.4) and humans (table 1.5) experience when exposed to hydrogen sulfide. The characteristic rotten egg odor cannot provide sufficient warning of high concentrations because hydrogen sulfide overwhelms the sense of smell. Thus one's ability to smell is diminished during exposure to hydrogen sulfide. (ASABE, 2006)

Table 1.4. Hydrogen sulfide exposure symptoms for swine. Adapted from ASABE (2006).

H_2S Concentration, ppm	Exposure Duration	Symptom
20	Continuous	Fear of light Loss of appetite Nervousness
50-240	Continuous	Vomiting Diarrhea
800+	Acute	Sudden nausea Unconsciousness Death

Table 1.5. Hydrogen sulfide exposure symptoms for humans. Adapted from ASABE (2006).

H_2S Concentration, ppm	Exposure Duration	Symptom
0.005		Barely detectable
4		Easily detectable Moderate odor
10		Eye irritation
27		Pungent odor
100	2-15 minutes	Coughing Loss of smell
200-300	> 60 minutes	Eye inflammation Respiratory tract irritation
500-700	30-60 minutes	Loss of conciousness Possible death
800-1000	Acute	Rapid unconciousness Stopped breathing
1000	Acute	Diaphragm paralysis Asphyxiation

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CHAPTER 2. A WIRELESS SENSOR NETWORK TO QUANTIFY HYDROGEN SULFIDE CONCENTRATIONS IN SWINE HOUSING

To be submitted to *Applied Engineering in Agriculture* for publication

R.J. Swestka, R.T. Burns, L. Tong, S.J. Hoff, N. Keren, H. Xin, H. Li, R.V. Muhlbauer

Abstract

The dynamic changes of in-barn H_2S concentrations during manure slurry agitation and pumping events, necessitates near-simultaneous monitoring of multiple points. This can be accomplished with sensors that can respond to very high (100-500 ppm) H_2S concentrations. This paper describes how this was accomplished through the use of electrochemical sensors paired with a wireless data transmission network. This wireless sensor network provided H_2S concentration data from multiple locations without the delay associated with sequential sampling of a mobile lab. The objective of this project was to develop a wireless H_2S sensor network that could be used to characterize the spatial distribution of H_2S in deep-pit swine production facilities associated with manure removal or agitation activity. The wireless H_2S sensor network developed in this project was easily transported, installed, and operated by one person; had an H_2S detection range of 0-500 ppm; 0.2 ppm system resolution; and a ±25.1 ppm system uncertainty. The network was verified to a range of 100 m with no signal interference issues. A 12 sensor system had a total component cost of $12,527. This network enabled researchers to monitor deep-pit swine barns during slurry removal on a scale not feasible with a mobile lab.

Keywords. Wireless Sensor Network, WSN, hydrogen sulfide, swine manure agitation, Zigbee.

Introduction

In deep-pit swine facilities, commonly used in the Midwestern U.S., the pigs are housed on slatted floors above the manure storage area. Throughout the production cycle, human caretakers frequently enter the swine barn. Hazardous high concentration hydrogen sulfide (H_2S) burst releases have been known to occur during swine manure slurry agitation in deep-pit facilities. Slurry agitation is necessary to suspend the settled solids for removal from storage. Because of H_2S burst releases during slurry agitation, dangerous conditions can exist in the swine barn. Although it is never recommended a human enter a swine barn during slurry agitation, entries still occur.

Chronic exposure to H_2S has been shown to cause respiratory problems and other illnesses in humans. Acute exposure to high concentrations, possible during slurry agitation and removal events, could lead to death (Donham et al., 1982; Donham and Gustafson, 1982). Hydrogen sulfide poisoning is also known to occur in swine. Swine losses to H_2S poisoning have occurred even when precautions were taken to avoid loss (Puck 2008). Custom manure applicators reported when swine loss was localized to an area, insufficient ventilation or unfavorable airflow patterns that allowed accumulation of H_2S was suspected to be the cause. This observation has demonstrated the need to investigate H_2S temporal and spatial distribution within deep-pit swine housing during manure slurry agitation and removal events.

The burst release characteristic of H_2S gas release is extremely hazardous. Past studies have shown that H_2S levels rapidly reached lethal concentrations during agitation of manure in deep-pit swine barns (Ni et al., 2000; Muhlbauer et al., 2008; Patni and Clarke, 2003). Although mobile labs containing gas analysis equipment have been shown to be highly accurate (Gates et al., 2009; Hoff et al., 2006; Ni et al., 2000; Ni et al., 2002; Moody et al., 2008), they have several limitations including: installation time, low mobility of sampling locations, and sequential sampling. Short duration bursts could be concealed due to the time interval and stabilization period associated with sampling multiple locations utilizing a mobile lab (Ni et al., 2000). The dynamic environment during slurry agitation necessitates multi-location and near-simultaneous H_2S measurement and subsequent data transmission to a central location.

Muhlbauer et al. (2008) demonstrated an electrochemical sensor could measure hydrogen sulfide within ±5% full scale accuracy of a pulsed fluorescence analyzer (Model 45C, Thermo Environment Instruments) up to 500 ppm H_2S during swine slurry agitation events. Multiple electrochemical sensors interfaced with a wireless data network would allow multi-location, near-simultaneous data collection without the infrastructure requirements of a mobile lab. This paper describes the development of a wireless H_2S sensor network to quantify H_2S concentrations associated with manure removal or agitation activity within deep-pit swine housing.

Safety Emphasis

The wireless H_2S sensor network was used to collect concentration data in deep-pit swine buildings before, during, and after manure agitation and removal events. Entry into a swine facility during slurry agitation or removal is never recommended. The H_2S concentration data collected using this wireless sensor network was used to assess the exposure risk associated with hydrogen sulfide before, during, and after manure slurry agitation and removal events (Swestka et al., 2010). H_2S distribution maps were developed to characterize concentration gradient across a barn during slurry agitation and removal events (Swestka et al., 2010).

Hydrogen Sulfide Gas Sensor

The wireless H_2S sensor network was designed to measure multi-location, simultaneous H_2S within a swine facility and to transmit the data to an outside location where an operator could monitor the conditions real-time. The wireless sensor network (WSN) consisted of multiple H_2S gas sensors combined with a wireless data communications network for remote monitoring and data storage.

Performance Test Method

Muhlbauer et al. (2008) tested multiple commercially available H_2S sensors for response time, accuracy, and repeatability in a controlled laboratory environment. The Pem-Tech PT295 HEC H_2S (Pem-Tech Inc., Sugar Land, TX) electrochemical H_2S sensor was shown to perform within five percent of a lab grade H_2S analyzer (Model 45C, Thermo Environment Instruments) in both controlled lab and sub-floor slurry storage swine barn environments. The same model sensor used in this network was used by multiple slurry applicators from October 2007 to December 2009. The sensor had a 1 ppm detection limit, 0 to 500 ppm range, and ±25 ppm accuracy. This range could capture the high concentration bursts shown to be possible during slurry agitation and removal events from sub-floor swine slurry storages (Muhlbauer et al., 2008; Patni and Clarke, 2003; Ni, et al., 2000). The sensor had a linear 4-20mA analog current output for integration with a data transmission network.

During initial phases of this project, the sensor was tested for drift in a controlled environment within a fume hood at the Iowa State University Agricultural Waste Management Laboratory. To perform the extended exposure test, the H_2S sensor was exposed to 100 ppm H_2S (Matheson Tri-Gas, Montgomeryville, PA) for 10 hours. The test circuit, shown in figure 2.1, was employed to evaluate the sensor. A digital dilutor controlling a zero air generator (produced clean, dry air free of SO_2, NO, NO_2, O_3, H_2S) was used to expose the sensor to a continuous airstream of 0 ppm (herein referred to as zero air) when necessary. The test circuit consisted of Teflon tubing and Teflon coated electric solenoids. A switch controlled the solenoids to switch between zero air and 100 ppm H_2S. An in-line humidifier was installed as recommended by the sensor manufacturer for prolonged testing utilizing compressed air. The sensor output was recorded every 10 seconds using a Campbell Scientific CR10X data logger (Campbell Scientific Inc., Logan, UT).

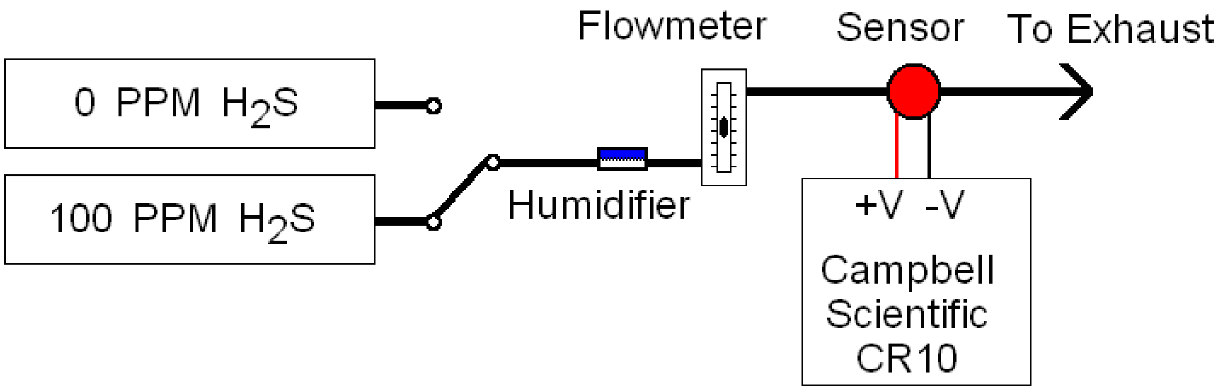

Figure 2.1. The lab test circuit for H_2S drift testing utilized a zero air generator (0 ppm) and certified H_2S cylinder (100 ppm) to test sensor performance.

An internal heater within the sensor head was allowed to warm for two hours, as directed by the sensor manufacturer, before calibration and testing commenced. After two hours the sensor was calibrated using 100 ppm H_2S prior to testing. The sensor was first exposed to zero air to record the baseline output. A continuous stream of 100 ppm H_2S was then introduced to the sensor for 10 hours for a total exposure of 1,000 ppm-hours. After 10 hours, the sensor was exposed to zero air for eight hours to allow the sensor to stabilize. After stabilization, the sensor was burst challenged for five minutes with 100 ppm H_2S. After five minutes had passed, zero air was applied to the sensor until it returned to the baseline output. These burst challenges were repeated in triplicate. The H_2S sensor was then recalibrated and again triplicate burst challenged for five minute bursts with 100 ppm H_2S.

Performance Test Results

The maximum sensor measurement error experienced was six percent during extended exposure testing. Figure 2.2 illustrates sensor performance during extended exposure to 100 ppm H_2S. Throughout the majority of the test the sensor output was 99 ppm, this equated to a one percent error from the sensor's calibration. The flow of H_2S was interrupted for two minutes to refill the in-line humidifier 5.5 hours into the test. The sensor returned to 99 ppm when flow was restored. Within one minute of zero air application the sensor registered one ppm, but immediately returned to 15 ppm. This return to 15 ppm could be an indication the sensor was beginning to become saturated with H_2S. The sensor output gradually decreased to zero ppm within 1.25 hours.

After the extended exposure testing, the sensor was tested with 100 ppm H_2S bursts. The sensor output was compared to burst challenges before and after a subsequent recalibration. The average of each triplicate burst challenge before and after recalibration is shown in Figure 2.3. The sensor demonstrated similar performance before and after recalibration, reaching T95 (95% of 100 ppm H_2S) in less than 1.5 minutes of applying 100 ppm H_2S. After zero air was applied the sensor returned to zero in less than 2.5 minutes during before and after recalibration tests.

Wireless Data Transmission Network

Initially a plug and play system was purchased to interface to the H_2S gas sensors. However, the system did not function correctly and the lack of technical support from the manufacturer made this system a nonviable option. A search for alternative network systems resulted in the team selecting a Zigbee wireless mesh network system for implementation in this project.

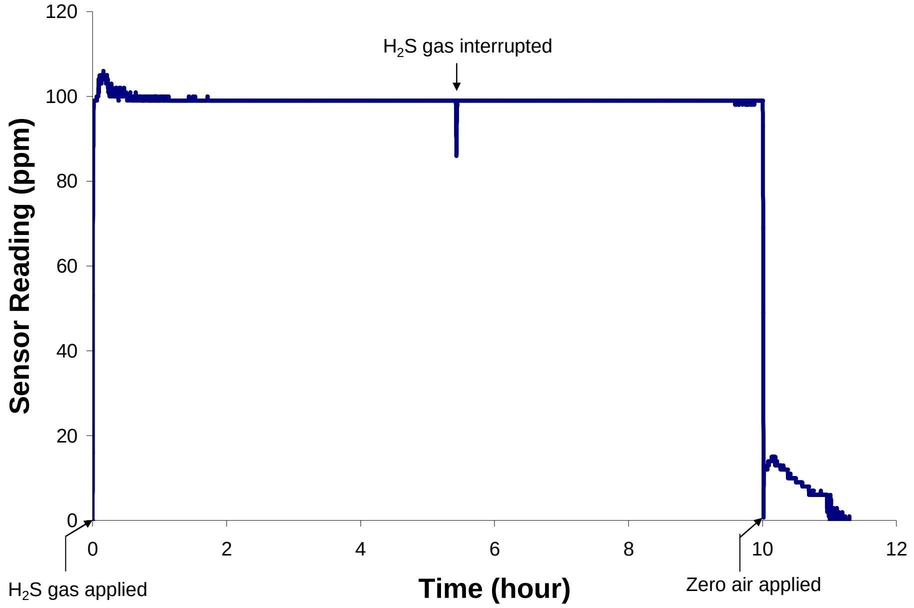

Figure 2.2. Pem-Tech PT295 HEC H_2S sensor output during extended exposure test, totaling 1,000 ppm-hours. 100 ppm H_2S gas was applied at time = 0 and zero air at time = 10 hours. Measurements were recorded in 10 second intervals.

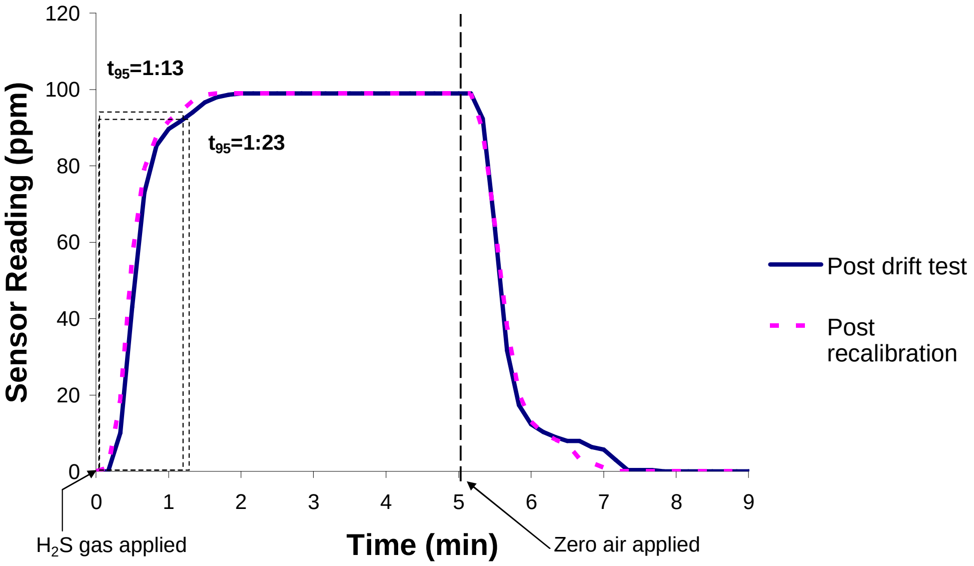

Figure 2.3. Pem-Tech PT295 HEC H_2S response time to 100 ppm H_2S after 1,000 ppm-hours use and after subsequent recalibration. 100 ppm H_2S gas was applied at time = 0 and zero air at time = 5 minutes. Measurements were recorded in 10 second intervals.

Zigbee Wireless Network System

Advances in mesh networking technology have led to their implementation in agricultural applications (Darr and Zhao, 2008; Coates and Delwiche, 2008). In a wireless mesh network, each node can communicate with any other node. If the sink and node are not within the transmission range, they communicate via hops through other nodes (figure 2.4).

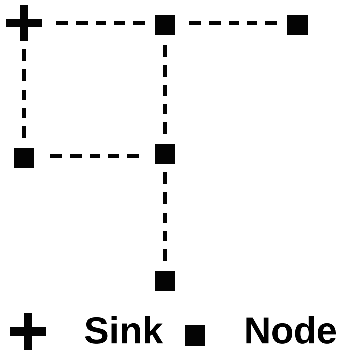

Figure 2.4. A schematic of a wireless mesh network.

Previous researchers (Hebel, 2006; Hebel et al., 2007; Darr and Zhao, 2008) utilized wireless mesh network systems employing the Zigbee standard. Zigbee was developed based on the IEEE 802.15.4 communication protocol (IEEE, 2003) it was designed for long battery life, data rates less than 250 kb/s, and low cost applications. The advantages of wireless mesh networks are range and reliability is increased with the addition of nodes between one another to forward data to the sink (Held, 2005, pp. 16-17).

Darr and Zhao (2008) developed a wireless data acquisition system using commercially available Zigbee mesh network modules (ETRX2-PA, Telegesis) to monitor temperature variation in swine barns. For this project Darr and Zhao provided access to the original system design that had been proven to perform in a swine housing environment. The ETRX2-PA module had 2 analog to digital conversion (ADC) ports and 12 digital I/O ports. One ADC port was utilized for the analog output of the H_2S sensor. Signal conversion was required since the 12-bit ADC (1.2 vdc full scale range) required a voltage input and the H_2S sensor utilized a linear 4-20mA current. A resistor (±0.1% accuracy) was installed as the load of the H_2S sensor output. The voltage potential across the resistor was monitored using the module ADC (figure 2.5). A 3 vdc voltage regulator was installed on the node to provide power. The voltage regulator accepted any 4.3-16 vdc power source and regulated it to 3 vdc for input to the ETRX2-PA module. This node design allowed connection to any sensor with a 4-20 mA signal and could be powered by a variety of commercially available batteries.

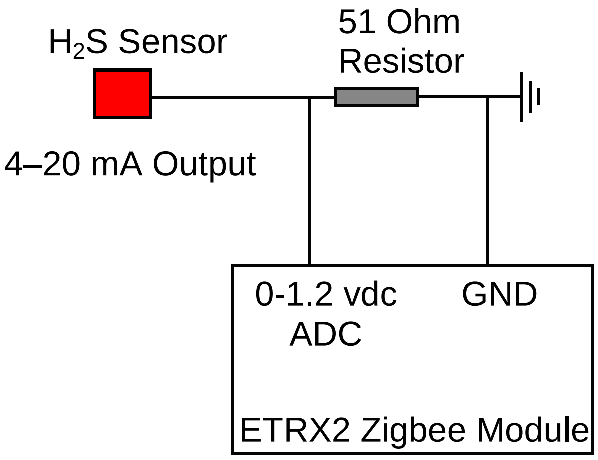

Figure 2.5. This circuit was used to convert the H_2S sensor linear 4-20mA output to a voltage signal for input to the analog to digital conversion port of the ETRX2 module.

To form a wireless sensor network, one ETRX2 module is configured as the Zigbee coordinator. This module is used as the data sink and is connected to the computer. Other ETRX2 modules are connected to the H_2S sensor, as shown in figure 2.5, to form nodes. These nodes are configured as a Zigbee router. The nodes read the sensor output and send data to the sink; the sink then forwards these data to the connected computer. The nodes and sink were configured to utilize the same communication channel within the wireless mesh network. These configurations are stored within the module's memory, thus communication began upon powering the network modules. The Zigbee protocol automatically finds the route nodes utilized to transmit data to the sink, routing messages through another node if the sink is out of range. The data transmission interval is user-programmable and was configured to 30 seconds. The nodes were configured to remain in full-power mode for two reasons: 1) the short-term monitoring period, and 2) increased network reliability. Network reliability was increased because the node was in a full-power state which permitted it to forward messages from other nodes to the sink. It was determined the 9 A-hr battery was sufficient to power the nodes for short-term monitoring.

Resolution and Uncertainty

The system has high resolution capabilities less than 1 ppm per binary level. The ADC has a 1.2 vdc full scale range and 12-bits of resolution combined with the linear sensor output yields a system resolution of 0.2 ppm per binary level. The ADC characteristics result in a quantization error of ±0.09 ppm. The H_2S sensor is the most significant contributor to the system uncertainty. The total system uncertainty is ±25.1 ppm. The H_2S sensor provides ±25 ppm of this uncertainty, the remaining uncertainty results from the signal conversion and ADC characteristics.

Network Range and Reliability

Intermediate nodes can forward the messages from nodes unable to directly reach the sink, thus the network range can be extended with more intermediate nodes. Darr and Zhao (2008) reported a theoretical maximum transmission range of 250 m due to the high transmittance characteristics of the module. This range is much greater than an expected range requirement of a typical swine production facility. The transmission range was tested to 66 m during the initial deployment of the system. This was the maximum distance which could be tested within this swine barn. During another monitoring event, the most distant node was located 100 m from the sink with intermediate nodes present. The network remained fully functional with no transmission issues in this deployment.

During all monitoring events, the network demonstrated excellent reliability and no signal interference. Due to the network architecture, when nodes attempt transmission at the same time only one node is permitted to do so. The other nodes wait until the transmission is complete before attempting to transmit again. A 0.5 second delay occurred when nodes attempted to transmit at the same time. This can be avoided by turning nodes on individually and allowing each node to establish a network connection before continuing to power the remaining nodes. During one monitoring event a sensor and node lost power, the fault was due to a loose connection to the battery.

Wireless Sensor Network Construction and Implementation

Wireless Sensor Network Construction

Wireless nodes and sinks were constructed using custom printed circuit boards, Zigbee mesh network modules, voltage regulators, and necessary resistors and capacitors. The sink was physically the same as a node; the difference is a modification within a programmable configuration register causing the module to be a sink or node. The nodes were sized to fit within the H_2S sensor enclosure which created a self contained unit that only required connection to a power source. A steel enclosure was constructed to hold a 12 vdc 9 A-hr battery; the H_2S sensor was then bolted to one side of the battery enclosure. Chains were attached to the top of the battery enclosure to suspend the entire unit from the ceiling or an overhead automatic feed distribution system (figure 2.6). Each monitored location within the swine barn included a sensor to monitor H_2S in the human occupied zone (HOZ), 1.5 m above the slat surface, and a sensor to monitor the animal occupied zone (AOZ), 0.1 m above the slat surface. One sensor at each location required extending the sensor wires to locate the sensor head assembly in the AOZ near the slat surface. These wires were routed through a PVC conduit to prevent the animals from damaging the wires. This extended sensor was secured to a swine pen using hose clamps. The sensor head assembly was protected from the swine by a PVC cap which prevented the pigs from biting or otherwise damaging the sensor head. This PVC cap was ported with multiple holes to prevent trapping the air within the cap.

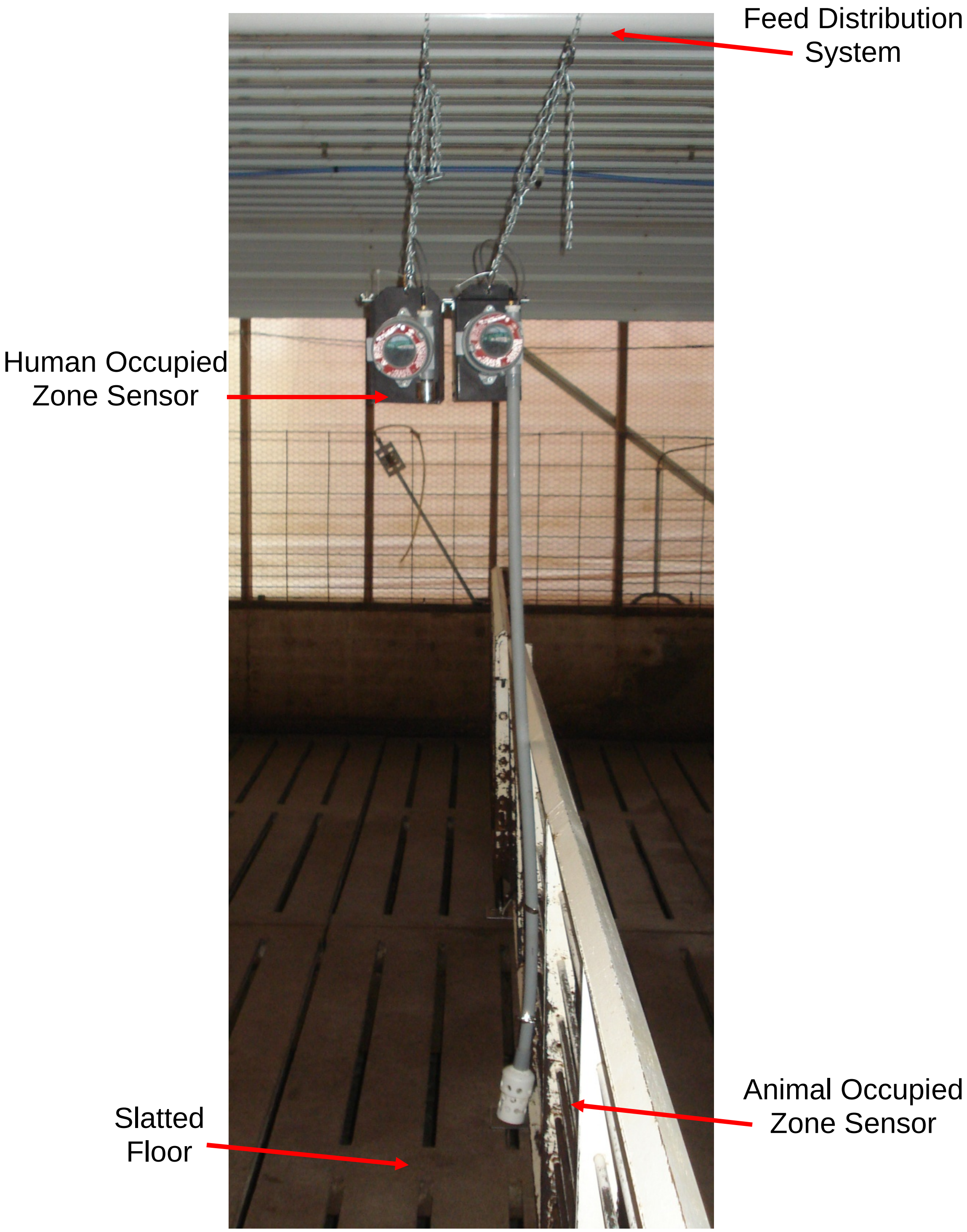

Figure 2.6. Installation of H_2S sensors in human and animal occupied zones utilized chains to suspend from overhead automatic feed distribution system. Hose clamps secured the animal occupied zone sensor to the swine pen.

Field Installation

The system was designed to be easily transported and quickly installed. A 12 sensor system can be transported in a minivan or pickup truck. Two trained individuals can install a 12 sensor system in a deep-pit swine barn in one hour, or one person in two hours. The preconfigured H_2S sensor nodes were installed suspended from the ceiling or overhead feed distribution system within the swine barn and the sink was retained outside for remote real-time monitoring. The sink was powered using an AC powered variable DC voltage generator. A computer was connected to the sink using a RS-232 connection. When the sink received a data transmission, the data was loaded to a buffer within the computer’s memory. A program operating on the computer monitored the buffer and attached a date and time stamp to the data and stored it on the computer’s hard drive. Access to 120 VAC, via electric service or a generator, was necessary to power the computer and variable DC generator.

When the system was removed the gas measurement nodes were sprayed with a disinfectant to address bio-security concerns. Between monitoring events at different sites the gas measurement nodes were sprayed with disinfectant and hot air dried for 30 minutes at 130 degrees Fahrenheit to eradicate potential pathogens.

Cost Analysis

The total cost of each wireless H_2S sensor node was $1,038. The gas measurement sensor was purchased from Pem-Tech Inc. (Sugar Land, TX) and powered using a 24 vdc converter connected to a 12 vdc 9 A-hr battery. The wireless nodes were assembled in the Iowa State University Embedded Systems

Laboratory using ETRX2-PA Zigbee wireless modules, electric components from Digikey International (Thief River Falls, MN), and a custom printed circuit board (PCB) from Advanced Circuits Inc. (Aurora, CO). Hardware, steel, and batteries were purchased from local suppliers.

Table 2.1. Unit cost of production for 12 wireless H_2S sensor units.

Description	**Unit Cost**
Pem-Tech PT295 HEC H_2S Sensor	$895
DC/DC Converter 24 vdc 2 W Output	$13
Telegesis ETRX2HR-PA 2.4 GHz Zigbee Transceiver	$31
Telegesis 2.4 GHz Zigbee Antenna & Connector	$20
Wireless node circuitry (PCB, resistors, capacitors, etc.)	$20
Steel, chains, wire, PVC, and hardware	$27
12 vdc 9 A-hr Battery	$32
Total Unit Cost	**$1,038**

As previously mentioned, any wireless module can be configured to a node or sink by changing configuration registers of the module. Due to this built-in functionality the cost of the sink was the same as a wireless node, $71. Unit cost for the wireless nodes could decrease as total number of nodes increases due to setup costs for custom printed circuit boards and bulk discounts for circuitry components. The DC voltage generator and computer were readily available, thus they are not included in this cost analysis.

Conclusion

A wireless sensor network based on currently available sensors and Zigbee wireless network technology was successfully developed. The network had a detection range of 1-500 ppm H_2S, system resolution of 0.2 ppm, and a system uncertainty of ±25.1 ppm. The sensor provided ±25 ppm of the uncertainty. The transmission range was proven to 100 m with no interference problems. A 0.5 second transmission delay was noticed when nodes attempted to transmit simultaneously. This can be avoided by turning nodes on individually and allowing each node to establish a network connection before continuing to power the remaining nodes. One person easily transported, installed, and operated the network. Following data collection, the network was removed, disinfected, and reinstalled at another swine facility. The built-in functionality of the Zigbee wireless module enabled user-programmable transmission intervals from 0.25 seconds to 4.5 hours. The 12 sensor system utilized Pem-Tech PT295 HEC H_2S electrochemical sensors and Telegesis ETRX2-PA Zigbee modules, and had a total cost of $12,527. The wireless sensor network provided a lower-cost measurement solution to a mobile lab. Opportunities arose to monitor a deep-pit swine manure pumpout event less than 12 hours prior; one person installed the network in the given time window with little difficulty in comparison to a mobile lab and tubing. This sensor network enabled researchers to monitor deep-pit swine barns during slurry removal on a scale not feasible with a mobile lab. The application of this sensor network will aid researchers to understand the dynamics of H_2S during manure agitation and removal in deep-pit swine housing.

Acknowledgements

The National Pork Board and the Iowa Pork Producers Association provided funds for this project. The authors would like to thank Dr. Matthew Darr and Dr. Lingying Zhao for their valuable assistance in Zigbee wireless network development.

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CHAPTER 3. SPATIAL DISTRIBUTION OF HYDROGEN SULFIDE IN DEEP-PIT SWINE HOUSING ASSOCIATED WITH MANURE SLURRY REMOVAL EVENTS: AN EXPLORATORY STUDY

To be submitted to *Transactions of the ASABE* for publication

R.J. Swestka, R.T Burns, S.J. Hoff, N. Keren, H. Xin, H. Li, R.V. Muhlbauer

Abstract

The objective of this paper is to explore the spatial distribution of hydrogen sulfide (H_2S) concentrations in deep-pit sow and finish swine facilities associated with pit agitation and pumping events. In-barn monitoring was performed in three finish swine and one sow gestation barn during manure removal events in the fall of 2009. A pulsed fluorescence hydrogen sulfide analyzer and wireless network of electrochemical sensors were used to collect H_2S concentration data during manure slurry pumpout events. Significant differences existed among H_2S concentrations based on horizontal and vertical locations in swine confinements during slurry agitation. The highest in-barn H_2S concentrations, 500 ppm, were recorded in deep-pit swine finish barns during aggressive manure slurry agitation where the agitation jet collided with a support pillar. The highest concentrations occurred early during manure agitation and maximum concentrations decreased as the event neared completion. The lowest peak in-barn H_2S concentration, 0.7 ppm, was recorded in a deep-pit swine sow gestation barn during manure pumping with no agitation. Areas near agitation activity and suspected areas of localized reduced ventilation

experienced higher H_2S concentrations than the remainder of the barn during manure pumpouts.

Keywords. Hydrogen sulfide, spatial distribution, swine manure agitation, swine and worker safety, deep-pit swine housing

Introduction

A typical swine confinement design in the Midwestern US is a deep-pit building with the animal occupied zone (AOZ) separated from the manure slurry storage area by a slotted floor. Dangerous conditions can be created in the AOZ caused by H_2S gas escaping the manure slurry storage area during slurry agitation. Furthermore, the rapid concentration increase of H_2S gas releases makes it hazardous. Studies have shown that H_2S levels can change rapidly reaching lethal concentrations in the AOZ during agitation of manure in sub-floor pits (Ni et al., 2000, Muhlbauer et al., 2008, Patni and Clarke, 2003).

Swine are sometimes present within the confinement during slurry agitation and removal events, and swine losses have occurred due to H_2S poisoning during these events. Custom manure applicators report that when swine loss is localized to an area away from the agitation source, insufficient ventilation (natural or mechanical) or unfavorable airflow patterns to prevent accumulation of H_2S is suspected to be the cause. Loss is also reported localized to the agitation source. This observation demonstrates the need to investigate the spatial variation of H_2S within swine housing during manure slurry agitation and removal events.

Muhlbauer et al. (2008) collected semi-continuous (less than one minute sampling interval) H_2S concentration data at two points within the same confinement simultaneously and concluded considerable spatial variation in H_2S concentration can exist in a swine confinement during slurry agitation. A recommendation from that study was to increase the number of sampling points to characterize the distribution of H_2S within a swine confinement.

Although a mobile lab containing gas analysis equipment is highly accurate (Gates et al., 2009; Hoff et al., 2006; Ni et al., 2000; Ni et al., 2002; Moody et al., 2008), it requires considerable resources to install and utilizes sequential sampling. Ni et al. (2000) concluded that the sequential sample method of a mobile lab can miss high bursts if they do not occur at a location that is currently being sampled. To prevent missing a burst, a wireless hydrogen sulfide sensor network, described in Swestka et al. (2010), collected semi-continuous H_2S concentration data from multiple locations within multiple barns. The concentration data was a “snapshot” in time of in-barn H_2S conditions during swine slurry pumpouts.

The objective of this paper is to explore the spatial distribution of hydrogen sulfide concentrations in deep-pit sow and finish swine facilities associated with pit agitation and pumping events.

Materials and Methods

Description of the Monitoring Equipment

The primary objective of monitoring the swine barns was to measure the in-house distribution of H_2S concentrations associated with deep-pit manure slurry pumping and agitation events. This was accomplished by monitoring H_2S concentrations with a matrix layout. A mobile air emissions monitoring unit (MAEMU) and fluorescence analyzer was used to monitor low H_2S concentrations (less than 20 ppm). A wireless sensor network of electrochemical sensors was used to monitor H_2S concentrations up to 500 ppm. These systems are discussed in the following sections.

Low Concentration Hydrogen Sulfide Measurement

A Mobile Air Emissions Monitoring Unit (MAEMU) housed a gas sample system, H_2S fluorescence analyzer, computer, and a data acquisition system. Project personnel previously designed and utilized this MAEMU to continuously monitor emissions from broiler facilities (Moody et al., 2008). At each sample location Teflon tubing (Fluorotherm FEP tubing) was routed from the barn interior to the MAEMU and connected to an individual supply pump. Each pump operated continuously, supplying air to the gas sample system. The computer controlled gas sample system allowed air from one location to the analyzer while the remaining samples would bypass analysis and be exhausted. The gas sample system was controlled by a LabView program that opened and closed solenoids to rotate samples on a programmed interval sampling each location within the barn. A paper filter inside the barn prevented large particulate matter from blocking the tubing and a Teflon filter inside the MAEMU prevented fine particulate matter from damaging the gas analyzer. The tubing was heat traced from the MAEMU to the barn interior to prevent condensation of the sample air.

A Teledyne API H_2S analyzer (Model 101E) (figure 3.1) had a maximum range of 20 ppm and a detection limit of 0.4 ppb. The unit was calibrated prior to use with 20 ppm H_2S calibration gas. The H_2S analyzer features an adjustable maximum measurement of 50 – 20,000 ppb and the option to use ppb or ppm units. Due to the potential for hydrogen sulfide bursts during manure slurry removal events, the maximum range (0-20 ppm) of the H_2S analyzer was selected. The analyzer output was logged every second with a National Instruments Compact Field Point and LabView program.

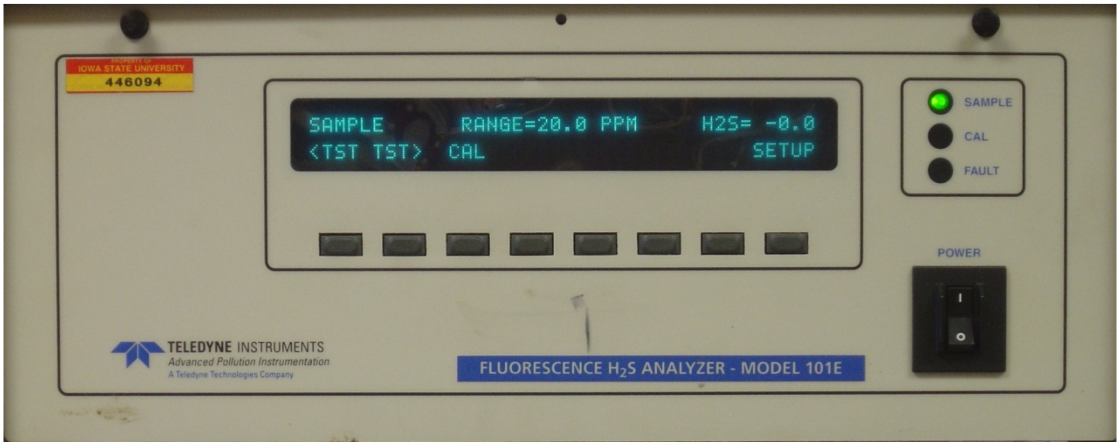


Figure 3.1. A Teledyne API Model 101E H_2S analyzer located inside the MAEMU measured H_2S concentrations of air inside the swine barn.

High Concentration Hydrogen Sulfide Measurement

A wireless sensor network of electrochemical H_2S sensors developed by Swestka et al. (2010) was used to monitor high concentration hydrogen sulfide. A total of 12 H_2S sensor units were supported from the ceiling or overhead automatic feed delivery system and monitored two heights at six locations within the barn. Each monitored location included a sensor at 0.1 m and 1.5 m above the slat floor, referred to as animal occupied zone (AOZ) and human occupied zone (HOZ) respectively. Each sensor transmitted H_2S concentration data every 30 seconds to a receiver connected to a computer located outside the swine barn.

Site Descriptions

Three deep-pit finishing and one deep-pit sow gestation barns located in Iowa were monitored during manure pumpout events in fall 2009. Data summarizing the barn and environmental conditions during these events is provided in table 3.1. Both the low and high concentration monitoring systems were installed at multiple sites. The concentrations at Sow Barn 1 were too low to register on the wireless sensor network, thus the network was not included in analysis of this barn. Additionally, high concentrations were recorded in Finish Barns 1 and 2, thus the MAEMU data was not included in analysis of these barns. The MAEMU was not installed at Finish Barn 3.

Finish Barn 1 (F1)

Finish Barn 1 was a 1,250 head hybrid ventilated deep-pit swine confinement. This barn had a 2.44 m deep pit for manure storage below a fully slatted concrete floor. The previous manure pumpout occurred spring 2009. Hydrogen sulfide concentration was monitored at two heights, 1.5 m and 0.1 m above the slatted floor, at each of the six locations shown in figure 3.2. A total of 12 sensors collected hydrogen sulfide concentration data within this barn during the pumpout.

Table 3.1. Conditions for each barn during manure pumpout.

Barn	**F1**	**F2**	**F3**	**S1**
Animal Type	Finish swine	Finish swine	Finish swine	Gestation sows
Animal Capacity	1,250	1,250	1,500	1,800
Prevailing Wind Direction	North	North	North-Northwest	North-Northwest
Wind Speed	16 kph (10 mph)	13 kph (8 mph)	29 kph (18 mph)	13 kph (10 mph)
Fans Active	2: 0.6 m pit 2: 0.6 m end wall	2: 0.6 m pit 2: 0.6 m end wall Interior stir fans	4: 0.6 m pit 2: 0.6 m end wall	11: 0.6 m pit 3: 1.3 m end wall
Curtains Status	Open: 1.2 m	Varied: <0.4 m	Open: 1.1 m	Closed
Pumpout Duration	5:23	3:45	8:00	14:50
Previous Pumpout	Spring 2009	Spring 2009	Fall 2008	Spring 2009
Number of Pumps for Agitation	2	2	2	0
Number of Tractors	2	2	2	0
Tractor PTO Power Rating	112 kW (150 hp) 116 kW (156 hp)	112 kW (150 hp) 116 kW (156 hp)	93 kW (125 hp) 93 kW (125 hp)	NA
Total Maximum Pump Capacity for Agitation	13,067 Lpm (3,452 gpm)	13,067 Lpm (3,452 gpm)	13,824 Lpm (3,652 gpm)	NA
Pump Pressure for Agitation	284.75 kPa (41.3 psi)	284.75 kPa (41.3 psi)	208.91 kPa (30.1 psi)	NA
Total Maximum Fluid Power for Agitation	62 kW (83 hp)	62 kW (83 hp)	47 kW (63 hp)	NA

* All barns oriented East-West

Sidewall curtains on the north and south side of the barn could be adjusted to allow air into the barn. Ceiling inlets within the barn also provided outside air into the barn. Four variable-speed 0.6 m pit fans and two fixed-speed 0.6 m end wall fans were available to exhaust air from the barn. During each of the first two ventilation stages, two pit fans operated at variable-speeds. When the end wall fans were active, the pit fans were operated at maximum speed.

During the pumpout two pit and two end wall fans operated at maximum speed and both sidewall curtains were fully open (1.2 m). Two tractor (1,000 rpm PTO) powered pump/agitators on opposing sides of the barn, cycled between filling application tanks and agitating slurry within the pit. Since both tractors did not operate at 100% rated engine speed and no data was collected on tractor performance or load applied to the tractor, actual fluid power of the agitation jets is unable to be calculated.

Since swine were not present within the barn the slurry applicators agitated more aggressive than if swine had been present. During subsurface and surface agitation the tractors powering the pumps operated at 75% rated engine speed. During surface agitation the discharge jet from the pump on the south side of the barn collided with a support pillar directly below the sensors at location 4. The operators abruptly adjusted tractor engine speed when cycling from filling slurry tanks to agitation.

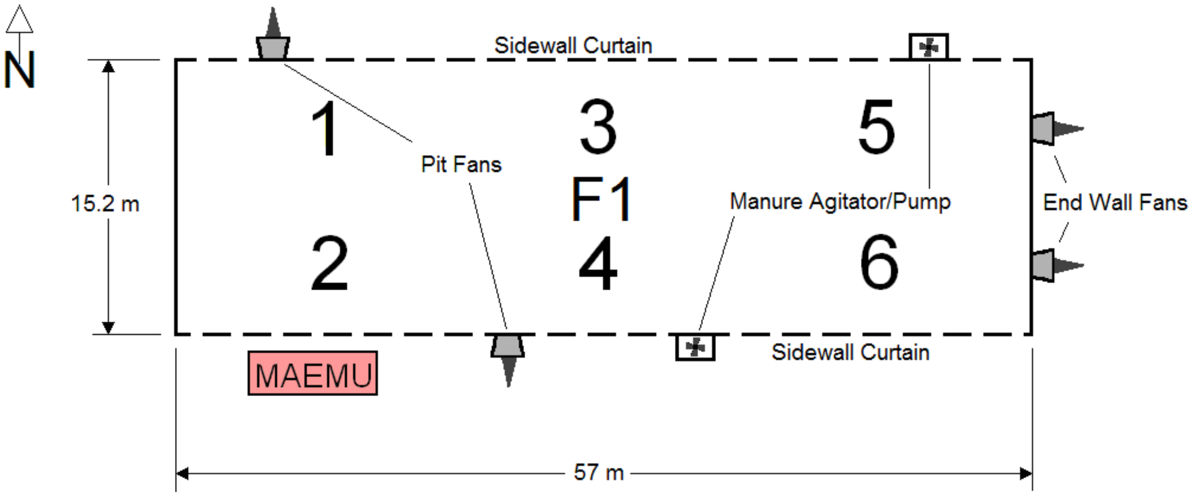


Figure 3.2. Layout of Finish Barn 1 and the wireless sensor network locations used to monitor hydrogen sulfide within this barn during the manure pumpout event.

Finish Barn 2 (F2)

Finish Barn 2 was a 1,250 head hybrid ventilated deep-pit swine confinement; it was located on the same site as Finish Barn 1. This barn had a 2.44 m deep pit for manure storage below a fully slatted concrete floor. The previous manure pumpout occurred spring 2009. Hydrogen sulfide concentration was monitored at two heights, 1.5 m and 0.1 m above the slatted floor, at each of the six numbered locations shown in figure 3.3. A total of 12 sensors collected hydrogen sulfide concentration data within this barn during the pumpout.

Sidewall curtains on the north and south side of the barn could be adjusted to allow air into the barn. Ceiling inlets within the barn also provided outside air into the barn. Four variable-speed 0.6 m pit fans and two fixed-speed 0.6 m end wall fans were available to exhaust air from the barn. During each of the first two ventilation stages, two pit fans operated at variable-speeds. When the end wall fans were active, the pit fans were operated at maximum speed.

During the pumpout two pit and two end wall fans operated at maximum speed and six interior stir fans mixed air in a counter clockwise direction within the barn. The sidewall curtains were manually adjusted periodically, but were never open more than 0.4 m during the pumpout. Two tractor (1,000 rpm PTO) powered pump/agitators on opposing sides of the barn, cycled between filling application tanks and agitating slurry within the pit. Since both tractors did not operate at 100% rated engine speed and no data was collected on tractor performance or load applied to the tractor, actual fluid power of the agitation jets is unable to be calculated.

The cooperating integrator desired to experiment with agitation and simulate cold environment conditions since swine were not present at the time of pumping. Upon beginning the pumpout, the slurry level was low enough that the agitation nozzle was immediately exposed to agitate the slurry surface and sidewall curtains were opened 0.2 m. The tractors powering the pumps operated at 75% rated engine speed. Approximately one hour later, the integrator closed the sidewall curtains and agitation was reduced to one pump, engine speed reduced to 50% of rated, and the agitation nozzle lowered below the slurry surface. This subsurface agitation regime continued until the agitation nozzle became exposed. When the nozzle became exposed both pumps resumed agitation at 75% rated engine speed and sidewall curtains were immediately opened 0.2 m. Approximately 25 minutes later the sidewall curtains were opened to 0.4 m. During both periods of aggressive surface agitation, the discharge jet from the pump on the south side of the barn collided with a support pillar directly below the sensors at location 6.

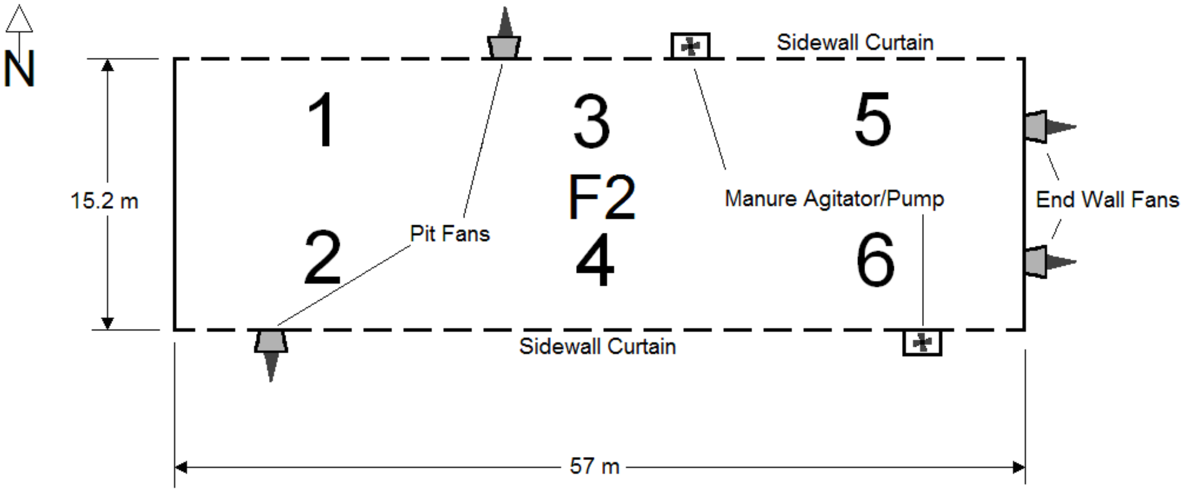


Figure 3.3. Layout of Finish Barn 2 and the wireless sensor network locations used to monitor hydrogen sulfide within this barn during the manure pumpout event.

Finish Barn 3 (F3)

Finish Barn 3 was a 1,500 head hybrid ventilated deep-pit swine confinement. This barn had a 2.44 meter deep pit for manure storage below a fully slatted concrete floor. The previous manure pumpout occurred fall 2008. Hydrogen sulfide concentration was monitored at two heights, 1.5 m and 0.1 m above the slatted floor, at each of the six numbered locations shown in figure 3.4. A total of 12 sensors collected hydrogen sulfide concentration data within this barn during the pumpout.

Sidewall curtains on the north and south side of the barn could be adjusted to allow air into the barn. Ceiling inlets within the barn also provided outside air into the barn. Six variable-speed 0.6 m pit fans and two fixed-speed 0.91 m end wall fans were available to exhaust air from the barn. When the end wall fans were active, the pit fans were operated at maximum speed.

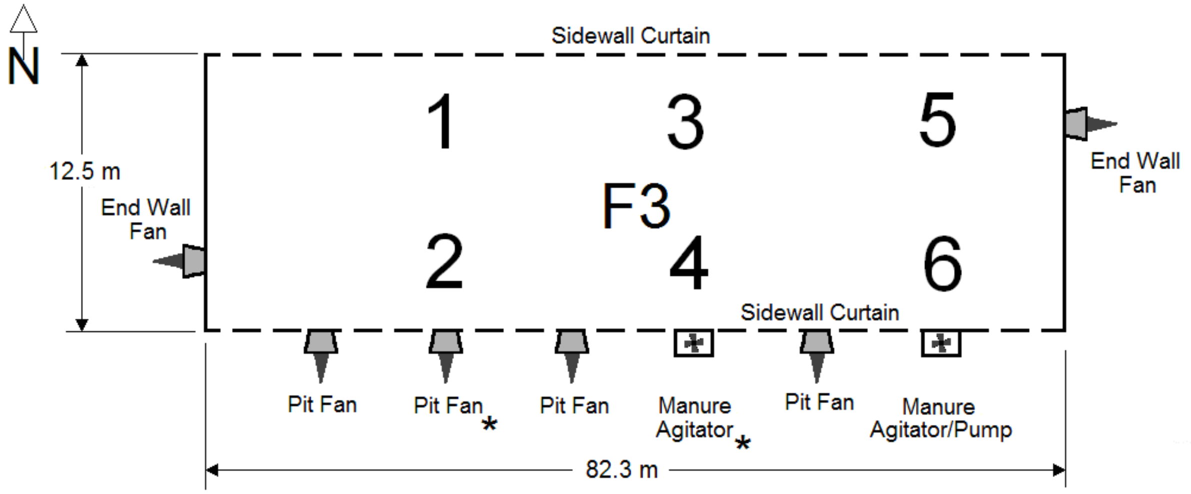


Figure 3.4. Layout of Finish Barn 3 and the wireless sensor network locations, indicated by numbers used to monitor hydrogen sulfide within this barn during the manure pumpout event. *The agitator near location 4 was moved to location 2.

During the pumpout four pit and two end wall fans were operated at maximum speed and both sidewall curtains were fully open (1.2 m). One tractor powered (1,000 rpm PTO) pump/agitator near location 4, continuously agitated slurry within the pit. Another tractor powered (1,000 rpm PTO) pump/agitator near location 6, cycled between filling application tanks and agitating slurry within the pit. When the slurry level lowered exposing the recirculation nozzle, the agitator near location 4 was removed and installed in place of the pit fan near location 2. A pit fan was then reinstalled at the access port near location 4.

Swine were present within the barn during the pumpout event. The tractors powering the pumps operated at 75% rated engine speed during agitation. Approximately one hour before the event ended, the agitator near location 2 was shutdown. Agitation continued near location 6 until the pumpout event was completed. Since both tractors did not operate at 100% rated engine speed and no data was collected on tractor performance or load applied to the tractor, actual fluid power of the agitation jets is unable to be calculated.

Sow Barn 1 (S1)

Sow Barn 1 was a 1,800 head mechanically ventilated deep-pit swine gestation confinement. This barn had a 3.05 meter deep pit for manure storage below a fully slatted concrete floor. Curtains covered the evaporative coolers on the north, south, and east walls of the barn. These curtains could be adjusted to allow air into the barn.

The curtains were closed during the pumpout event. Eleven pit and three end wall fans operated at maximum speed during the pumpout event. One trailer mounted engine driven pump was used to pump manure slurry from the pit and supply it to a drag hose manure injection system. No method to mix or agitate manure slurry was employed during this pumpout. Hydrogen sulfide concentration was monitored 1.5 m above the slatted floor at locations A, B, and C as shown in figure 3.5. Location D was in the pit headspace 0.1 m below the slatted floor. All samples were pumped through Teflon tubing to a pulsed fluorescence analyzer inside a MAEMU. Hydrogen sulfide concentration data were collected from a total of 4 locations within this barn during the pumpout. The wireless sensor network was installed in this barn but concentrations were below the detection limit for most of the event. Thus, for analysis only the MAEMU data was utilized.

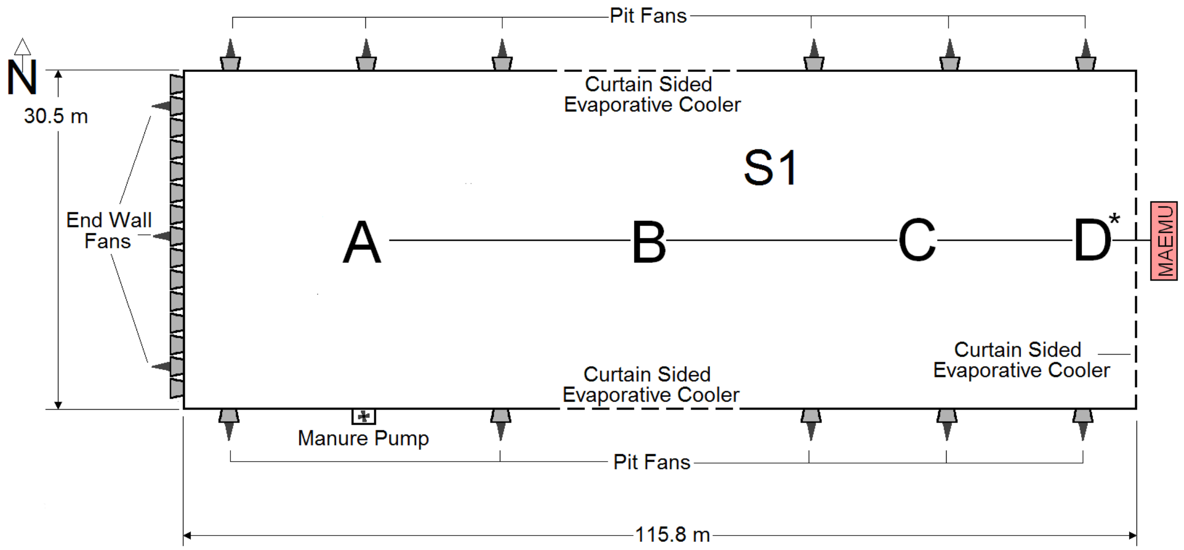


Figure 3.5. Layout of Sow Barn 1 during the manure pumpout event. The letters indicate the air sample locations for fluorescence analysis to monitor hydrogen sulfide within this barn. *Location D is in the pit headspace.

Data Collection and Analysis

The monitoring systems were installed prior to manure pumpout events. To conserve batteries for the event, the network was powered approximately 90 minutes before pumping began. This ensured the sensor’s internal heater had adequately warmed and representative data would be collected. Project personnel were notified of opportunities to monitor pumpout events sometimes less than 24 hours prior. The wireless sensor network proved beneficial when one person could install the system in the given time window with minimal difficulty in comparison to a mobile lab.

For the wireless sensor network, the data received from the sensors was grouped within a 30 second window to represent a snapshot of the H_2S concentrations in the barn. A set of rules was developed for dividing the data into snapshots of the barn. If the timestamp was within the first half minute, then the data was associated with the beginning of the minute (i.e. sensor timestamp = 1:28, then it is grouped with data representing time = 1:00). If the timestamp was within the last half minute, then the data was associated with the middle of minute (i.e. sensor timestamp = 1:58, then it is grouped with data representing time = 1:30).

The MAEMU system was programmed to switch sample locations every five minutes. Moody et al. (2008) documented the T95 (95% of the concentration) response time for the API 101E to be 75 seconds for 44 and 93 ppb H_2S. To prevent the data during the response time from causing a misrepresentative reading, the concentrations from the last 60 seconds of each 5 minute sample were averaged into a single concentration. This concentration was then treated as a singular measurement associated with the last minute of the sample. Concentrations between sample periods were linearly interpolated.

Each finish barn’s dataset was subdivided temporally to reflect before pumping, subsurface agitation, surface agitation, and after pumping. The sow barn dataset was subdivided temporally to reflect before pumping, during pumping, manual ventilation post pumpout, and auto ventilation post pumpout. A ten minute transition period between temporal periods was removed from the dataset due to residual effects of the previous period. Statistical analysis was performed with the MIXED procedure of SAS (SAS Institute Inc., Cary, North Carolina). The MIXED procedure was used to perform an analysis of variance (ANOVA) comparing concentrations from locations and heights within each barn. Time was treated as a random effect in all barns; location, position, and the interaction of location and position were fixed effects for the finish barns. Due to the lack of measurements in two heights at any location, location was the sole fixed effect for the sow barn. The Satterthwaite method was used to approximate degrees of freedom. For the finish barns, a difference among least squares means is an estimate of the differences of all locations and heights within the barn. For the sow barn, a difference among least squares means is an estimate of the differences of all locations within the barn. A Tukey-Kramer adjustment was used to account for different samples sizes within the dataset. At times the wireless sensor network had a 0.5 second delay caused by nodes attempting to transmit simultaneously. This caused some sensors to be excluded from a “snapshot” of the barn.

Manure nutrient analyses were gathered from all monitored barns for comparison. Records of recent manure analysis from all barns were requested. For barns lacking a recent manure nutrient analysis, Finish Barn 3 and Sow Barn 1, a sample of manure was collected. A cup sampler was used to collect samples from the top, middle, and bottom of the pit at three randomly selected access ports at Finish Barn 3 and Sow Barn 1. The samples were composited within a 20 L plastic bucket and thoroughly mixed. A one liter sample was collected from the mixture and shipped to Midwest Laboratories Inc. (Omaha, NE) for standard manure nutrient analysis.

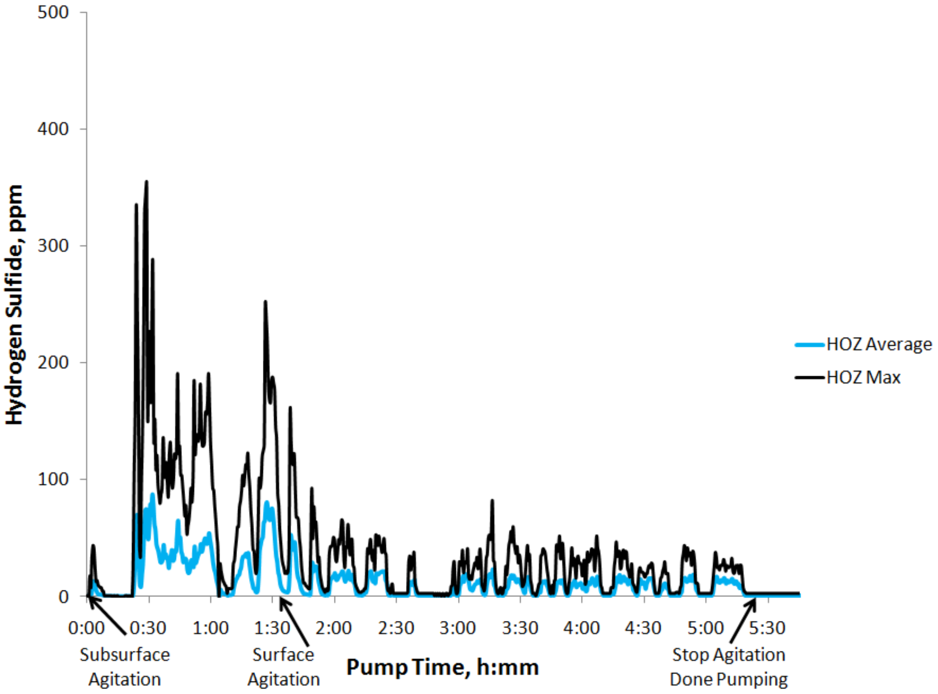
Results and Discussion

Concentration Ranges

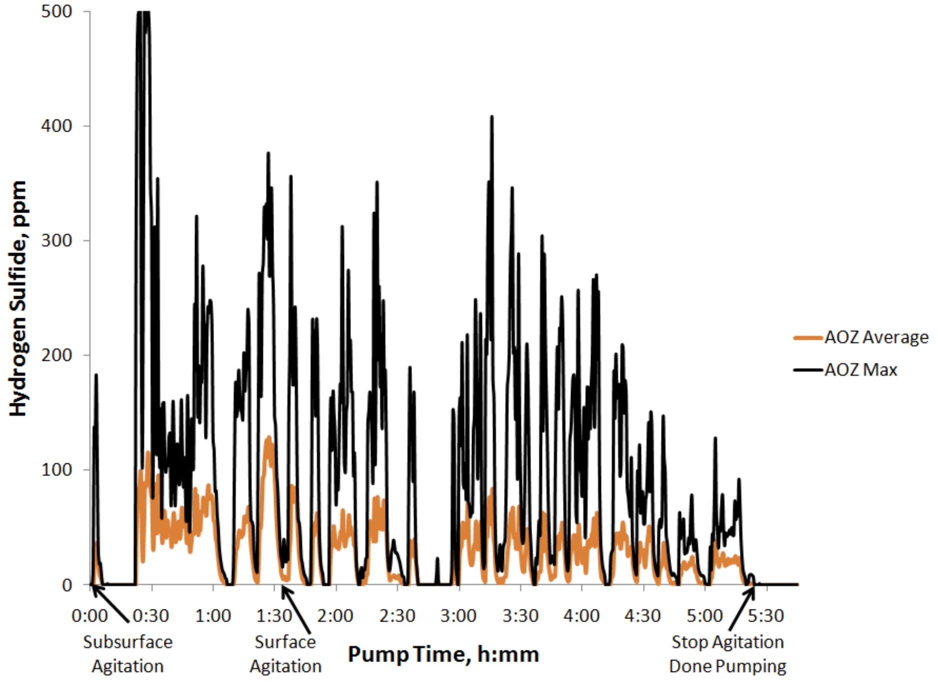
The average and maximum concentrations of H_2S in each zone for Finish Barn 1, 2, and 3, is illustrated in figures 3.6, 3.7, and 3.8 respectively. In examining concentrations in the barns it is quickly seen that concentrations change rapidly and were highly variable with respect to time. This dynamic cyclical change during agitation was attributed to the cycling action of turning agitation on or off to agitate slurry in the pit or fill application tanks as shown in figure 3.9. Also concentrations were substantially lower for Finish Barn 3. Of the 3 finish barns, this was the only barn where swine were present at the time of pumping. The results suggest that the operators used less aggressive agitation with swine present or the lower fluid power for agitation at Finish Barn 3 generated lower H_2S releases.

In Finish Barns 1 and 2 the maximum concentration recorded was 500 ppm occurring during aggressive subsurface (F1) and aggressive surface (F2) agitation. This is the upper detection limit of the sensor; the actual concentration could have been higher. Concentrations were significantly lower in the human zone than the animal zone for each finish barn. This suggests that H_2S concentrations are greater closer to the manure slurry surface. Also, as the pumpout event nears completion H_2S releases decrease in concentration. This suggests H_2S has been driven out of the slurry by agitation and as the event continues releases decrease. Furthermore, the potential for high concentration H_2S bursts is greatest at the beginning of the event before H_2S has been released out of the slurry.

The average concentrations and range of H_2S for the sow barn pumpout are shown in figure 3.10. In comparison to the concentrations in the finish barns during pumpouts, the hydrogen sulfide levels were dramatically lower. This suggests hydrogen sulfide concentrations can be maintained at very low levels during pumpouts by not agitating manure slurry.

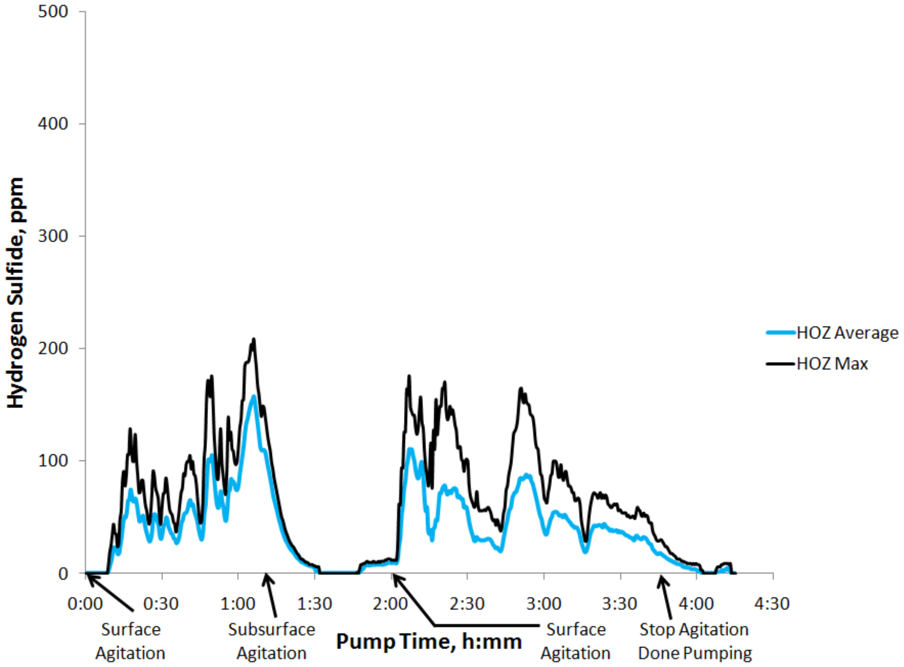


(a) Human occupied zone

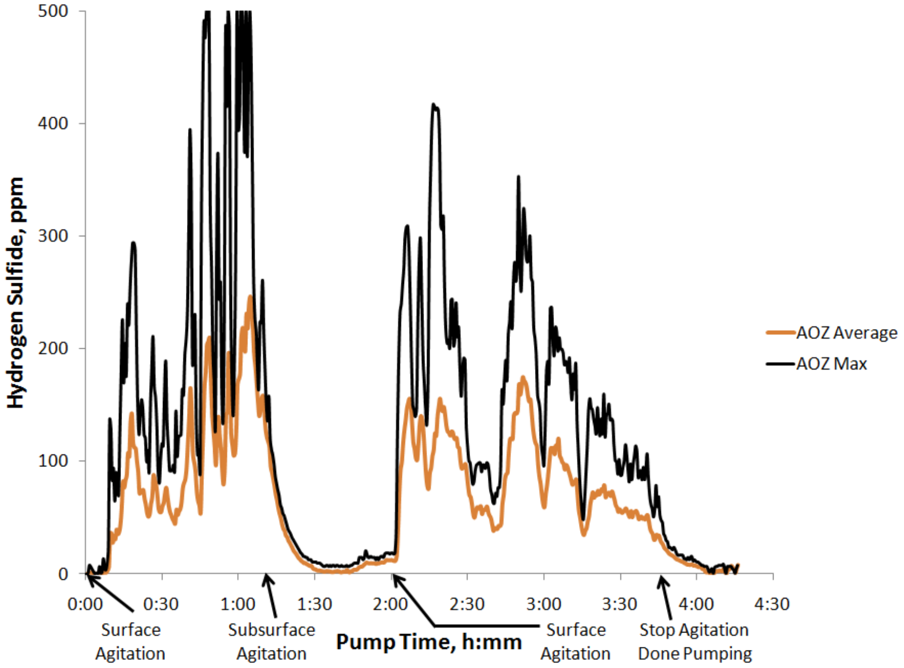


(b) Animal occupied zone

Figure 3.6. Average and maximum concentrations according to zone within Finish Barn 1 during each 30 s “snapshot”.

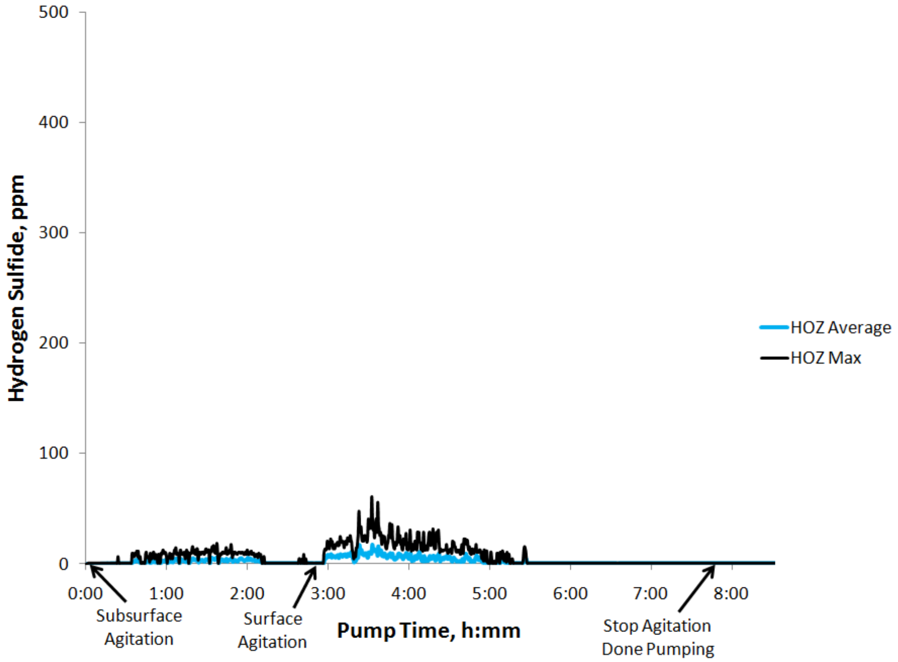


(a) Human occupied zone

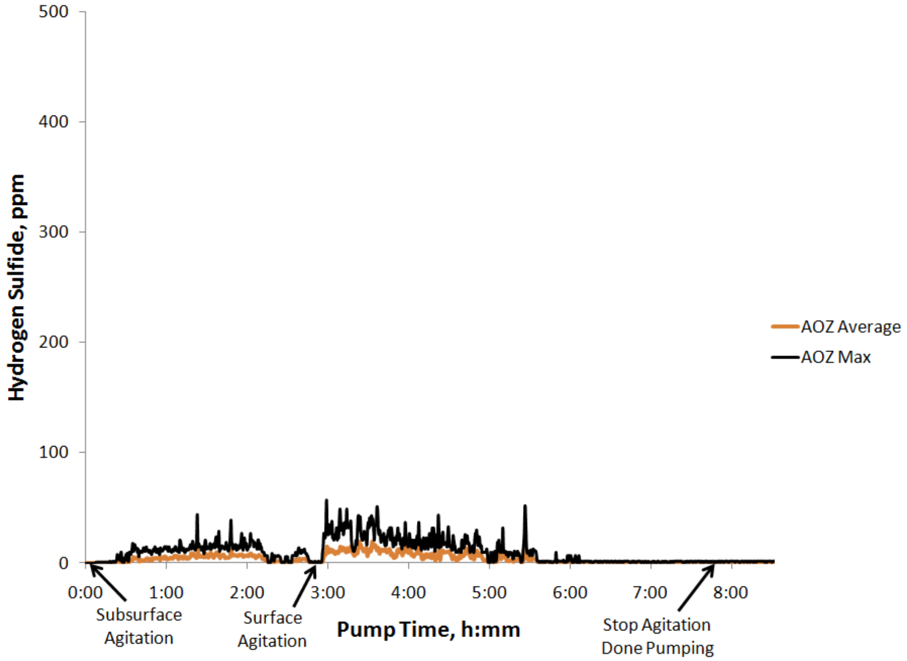


(b) Animal occupied zone

Figure 3.7. Average and maximum concentrations according to zone within Finish Barn 2 during each 30 s “snapshot”.

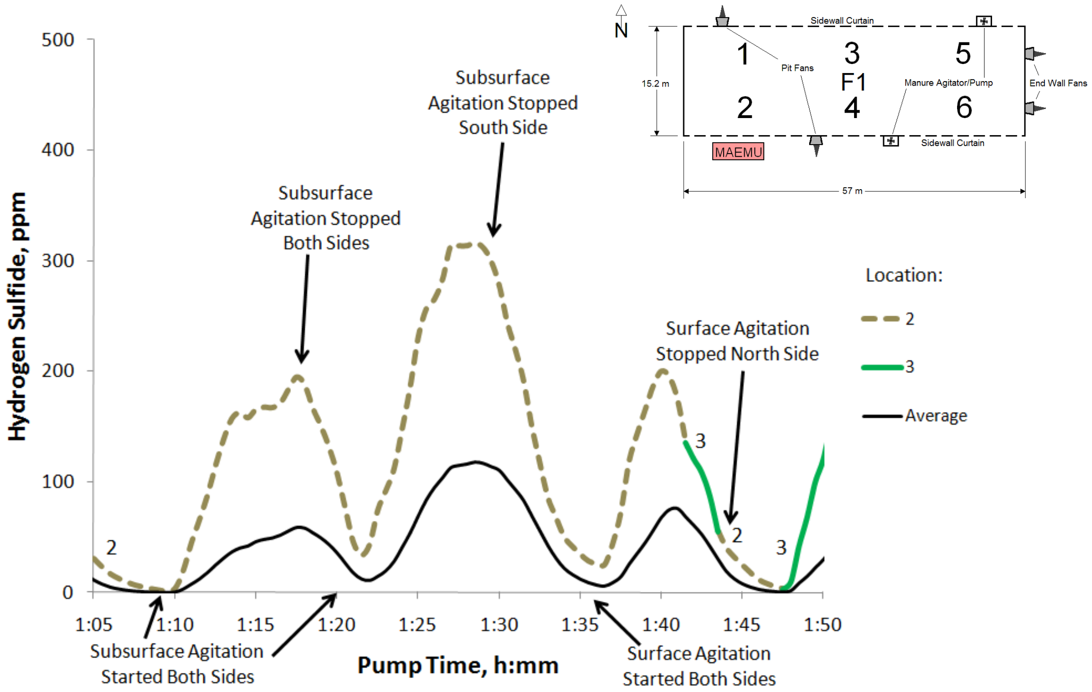


(a) Human occupied zone

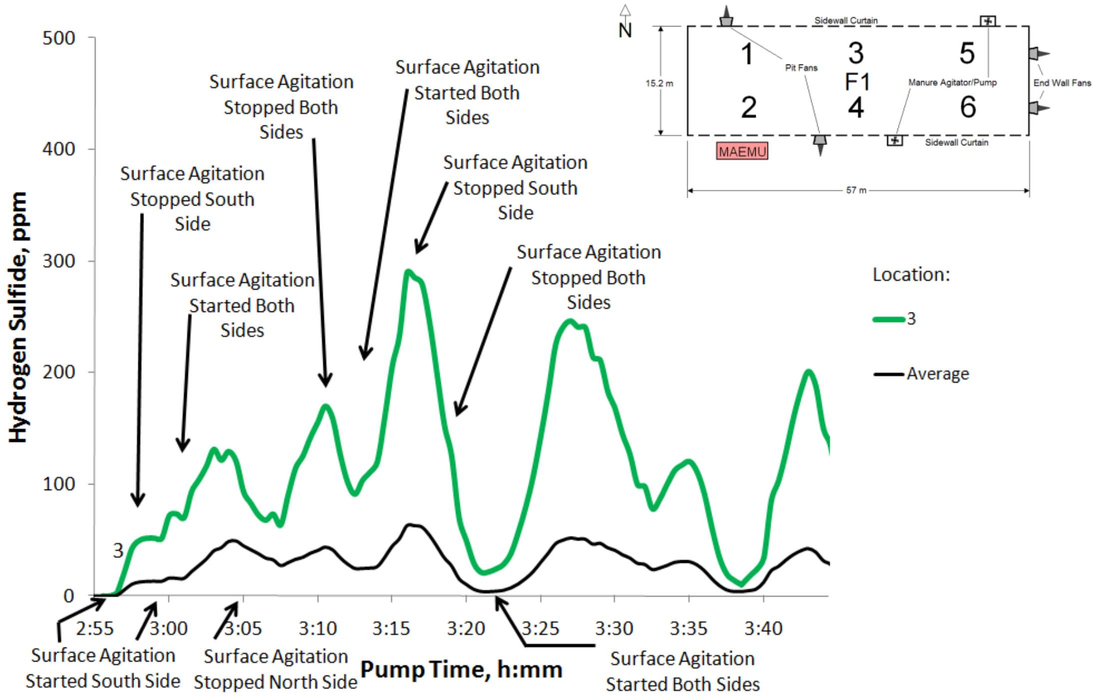


(b) Animal occupied zone

Figure 3.8. Average and maximum concentrations according to zone within Finish Barn 3 during each 30 s “snapshot”.



(a) Subsurface agitation



(b) Surface agitation

Figure 3.9. H_2S levels react to agitation activity, increasing and decreasing as agitation starts and stops. Animal zone data from Finish Barn 1.

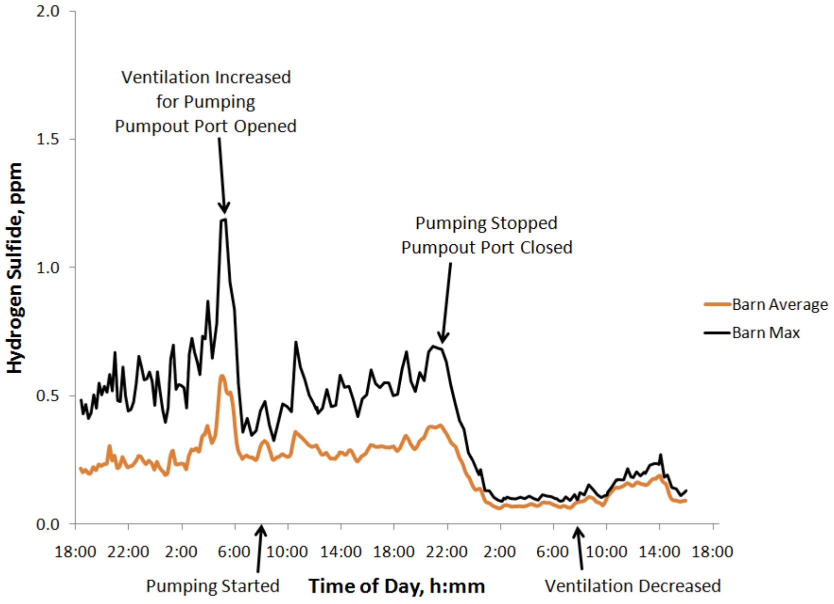


Figure 3.10. Average and maximum concentrations according to zone within Sow Barn 1 during each 30 s “snapshot”.

Spatial Distribution of Hydrogen Sulfide

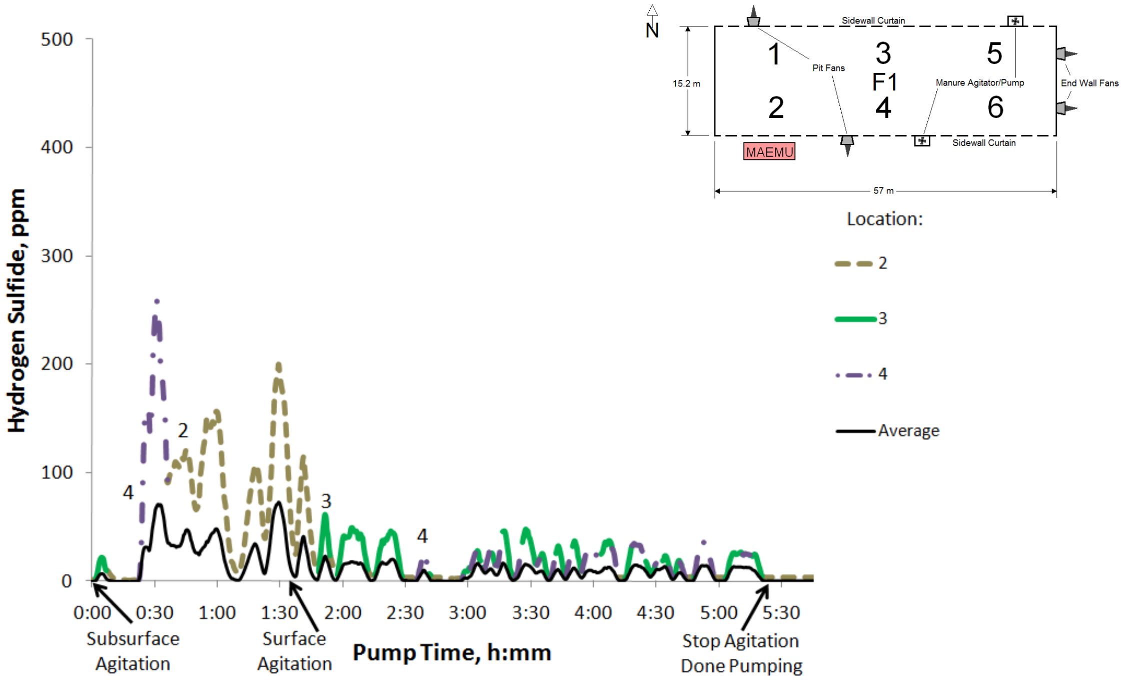
Finish Barn 1 (F1)

Hydrogen sulfide concentrations were monitored at multiple locations within each barn. The locations of the maximum concentrations in the human and animal occupied zones throughout the pumpout event in Finish Barn 1 are illustrated in figure 3.11. In examining both zones, the locations of maximum concentration align in both the animal and human occupied zones. As a general trend it appears the locations associated with maximum concentrations are near the agitation jet which collided with a support pillar.

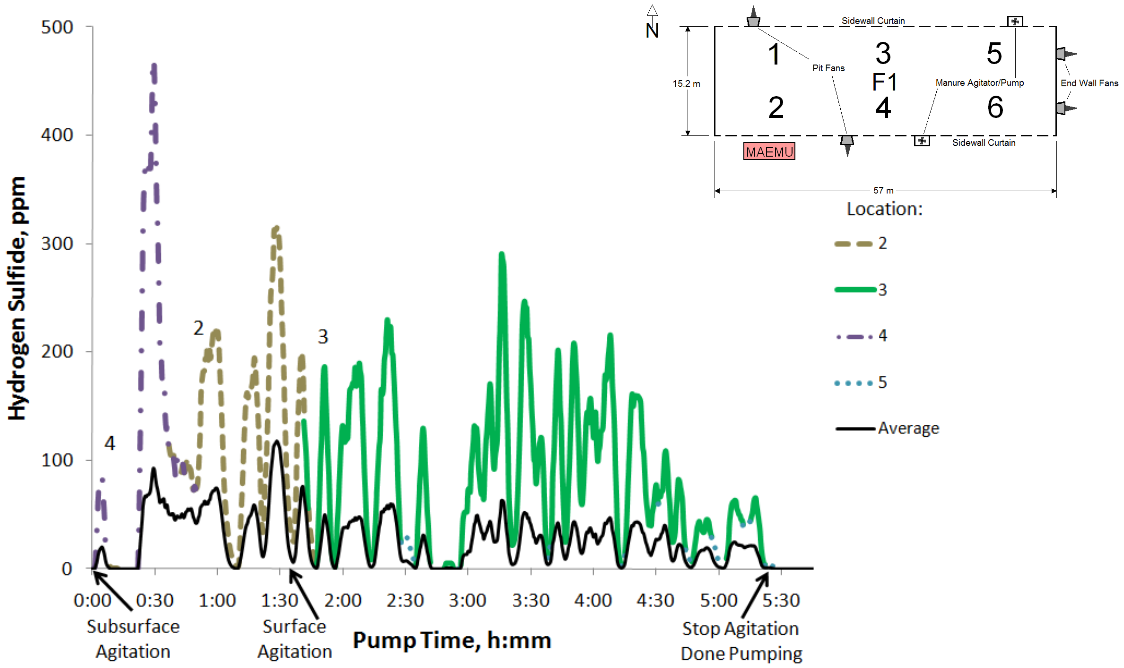
When examining the average concentration and standard error subdivided by time it is apparent concentrations are low before and after the pumpout event (table 3.2). Concentrations among locations and zones before and after the event were not significantly different. However, the exception is location 2 in the human zone. It was significantly different from all other monitored points in the barn. This can be explained by the environment and ventilation conditions. The MAEMU potentially obstructed wind on the leeward side of the barn possibly creating an area deficient in ventilation allowing H_2S to accumulate in this area. Site personnel observed no wind in this area, but did not collect an air velocity profile for the barn.

Concentrations increase greatly during agitation periods in comparison to non-agitation periods. This confirms other studies stating agitation of manure slurry releases H_2S thus increasing in-barn concentrations and emissions. Furthermore, significant interaction existed between all fixed effects during all subdivided time periods suggesting H_2S spatial variation is complex and varies considerably with respect to space. The standard deviation is large during aggressive agitation suggesting H_2S varies considerably with respect to time. Also, the H_2S levels at the location of maximum concentrations are much greater than the barn average (figure 3.11). Subsurface agitation resulted in higher peak and average concentrations because it was the first agitation period during this pumpout event (figure 3.12).

As a general trend the locations associated with highest peak concentrations are where manure slurry was disturbed via agitation (figure 3.12). This suggests H_2S is released from manure slurry via agitation.



(a) Human occupied zone



(b) Animal occupied zone

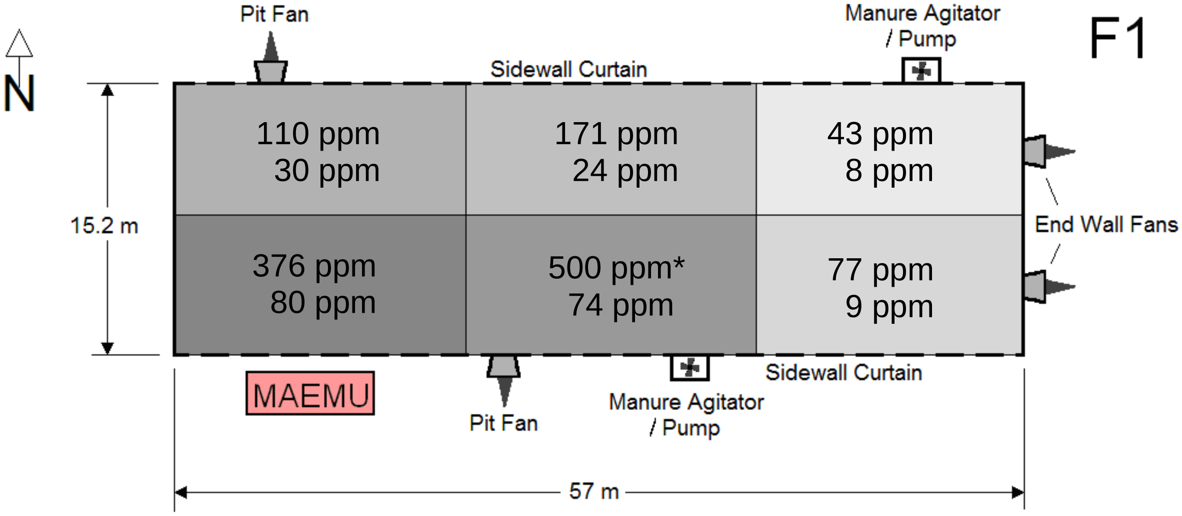
Figure 3.11. Maximum concentrations corresponding to location and zone within Finish Barn 1. Color and number indicate location within the barn.

Table 3.2. Average and standard error of the mean hydrogen sulfide concentration at each of the 12 monitored locations in Finish Barn 1 subdivided temporally.

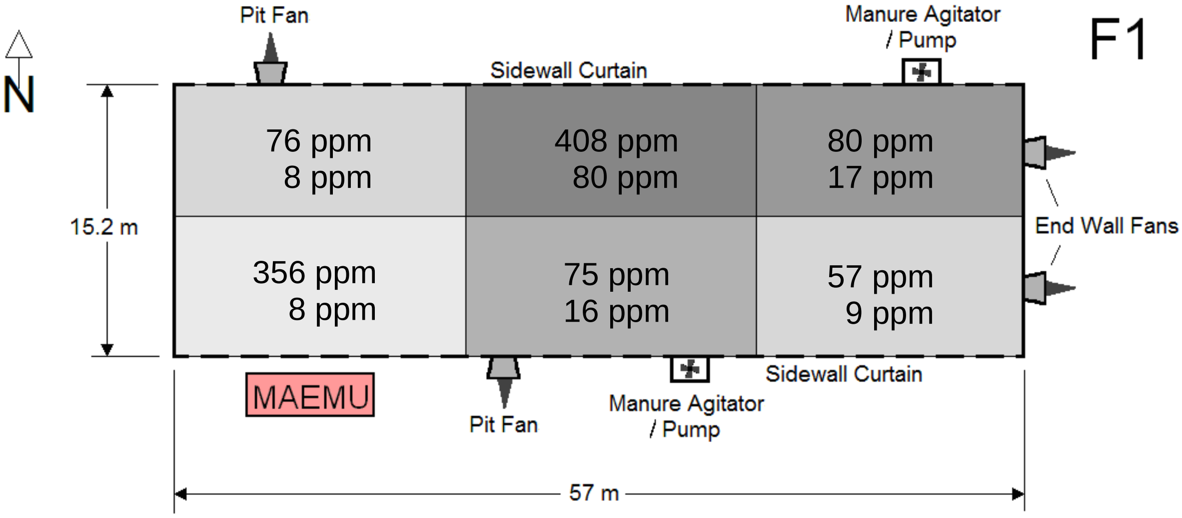
Height[†]	Location	Before Pumpout H_2S, ppm			Subsurface Agitation H_2S, ppm			Surface Agitation H_2S, ppm			After Pumpout H_2S, ppm		
		$\bar{x}$		*SE*	$\bar{x}$		*SE*	$\bar{x}$		*SE*	$\bar{x}$		*SE*
0.1	1	0.01	a	(0.02)	30.13	a	(4.06)	8.36	a	(1.36)	0.01	a	(0.04)
0.1	2	0.01	a	(0.02)	79.89	c	(4.06)	8.07	a	(1.36)	0.01	a	(0.04)
0.1	3	0.01	a	(0.02)	23.59	ae	(4.06)	79.60	d	(1.36)	0.01	a	(0.04)
0.1	4	0.01	a	(0.02)	74.00	cd	(4.07)	16.30	c	(1.36)	0.01	a	(0.05)
0.1	5	0.01	a	(0.02)	7.63	be	(4.06)	17.10	c	(1.36)	0.01	a	(0.04)
0.1	6	0.01	a	(0.02)	9.17	be	(4.07)	8.52	a	(1.36)	0.01	a	(0.04)
1.5	1	0.01	a	(0.02)	0.10	b	(4.07)	0.10	b	(1.36)	0.01	a	(0.04)
1.5	2	0.40	b	(0.02)	58.87	d	(4.07)	8.44	a	(1.36)	1.07	b	(0.04)
1.5	3	0.01	a	(0.02)	26.73	ac	(4.07)	18.12	c	(1.36)	0.01	a	(0.04)
1.5	4	0.01	a	(0.02)	44.35	ad	(4.07)	17.39	c	(1.36)	0.01	a	(0.04)
1.5	5	0.01	a	(0.02)	5.26	b	(4.07)	2.71	ab	(1.36)	0.01	a	(0.04)
1.5	6	0.01	a	(0.02)	6.05	b	(4.07)	3.85	ab	(1.36)	0.01	a	(0.04)
		n = 90			n = 172			n = 454			n = 85		

† Distance above slat floor in m

Different letters within a column indicate statistically significant difference ($P < 0.05$).



(a) Subsurface agitation



(b) Surface agitation

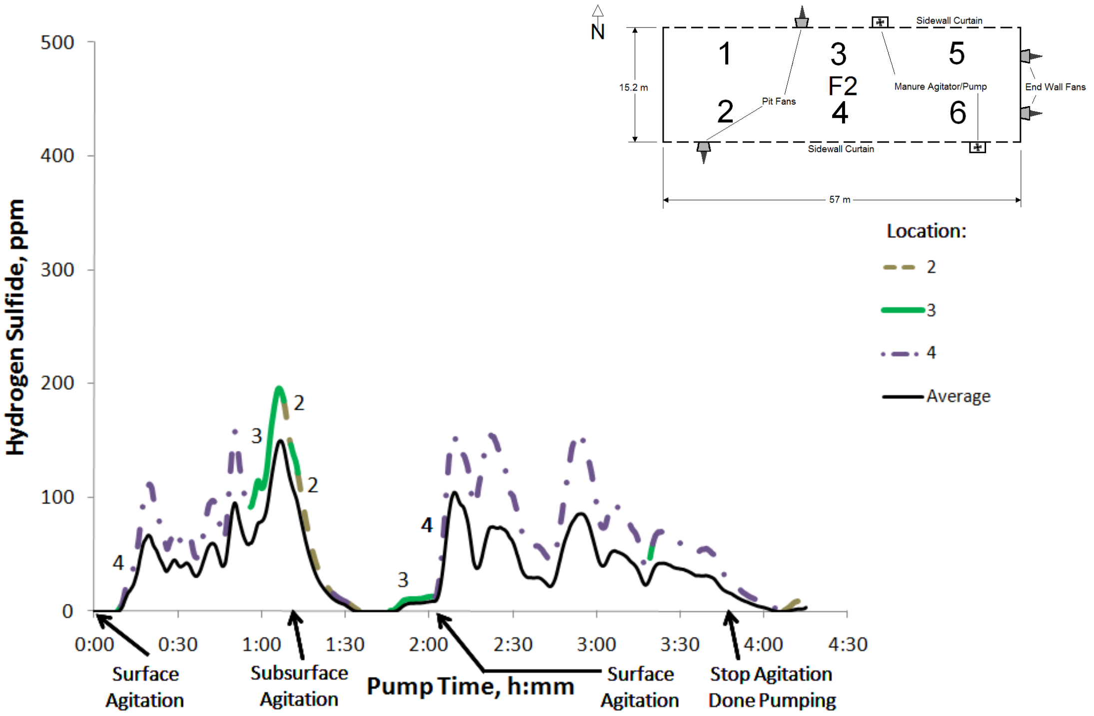
Figure 3.12. Spatial distribution of hydrogen sulfide in the AOZ of Finish Barn 1 according to agitation period. Color correlates to least squares means estimate for the location at animal level (darker indicates higher values). Values are the maximum (top) and least squares mean (bottom) concentration at the location for the specified time period. *Maximum detection limit of sensor.

Finish Barn 2 (F2)

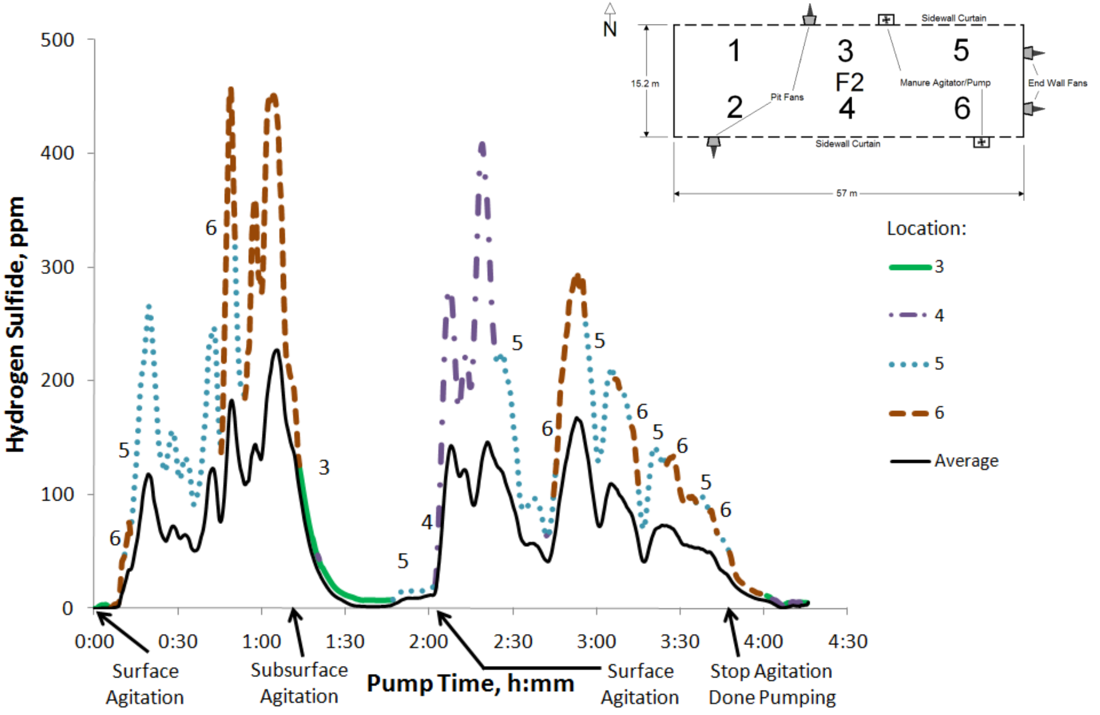
The location of the maximum concentration in the human and animal occupied zones throughout the pumpout event in Finish Barn 2 is illustrated in figure 3.13. The sensor at location 6 in the human zone failed to collect data during the entire pumpout event, thus it was removed from analysis. In examining the AOZ and HOZ, the locations associated with the maximum concentration do not align in both zones. Stir fans operated in the barn during this pumpout event mixing the air in the barn. The maximum concentrations in the HOZ were near the center of the barn suggesting stir fans moved the hydrogen sulfide from its burst source to other locations throughout the barn.

The hydrogen sulfide average and standard error concentration data subdivided temporally are shown in table 3.3. When examining the information it is evident concentrations are low before and after the pumpout event. Concentrations among monitored points within the barn were not significantly different before pumping began. After pumping ended no distinct pattern could be determined among significant differences for monitored points. However, average concentrations were higher near the east end of the barn where aggressive agitation occurred than the west end where no agitation occurred.

Concentrations increase greatly during the pumpout event confirming agitation of manure slurry releases hydrogen sulfide thus increasing in-barn concentrations and emissions. Furthermore significant interaction existed between all fixed effects during all subdivided time periods suggesting hydrogen sulfide spatial variation is complex and varies considerably with respect to space.



(a) Human occupied zone



(b) Animal occupied zone

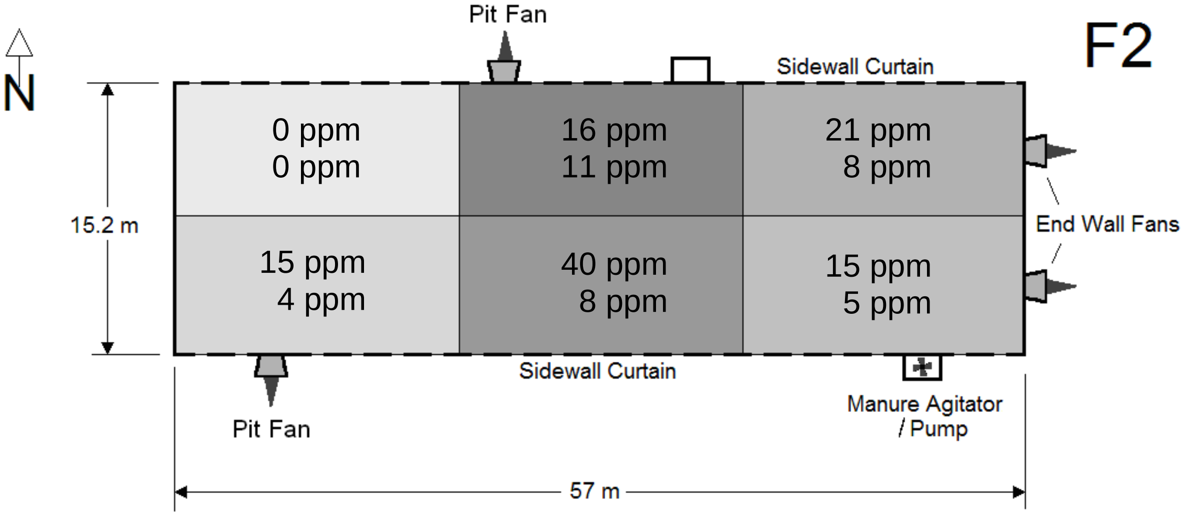
Figure 3.13. Maximum concentrations corresponding to location and zone within Finish Barn 2. Color and number indicate location within the barn.

Table 3.3. Average and standard error of the mean hydrogen sulfide concentration at each monitored location in Finish Barn 2 subdivided temporally.

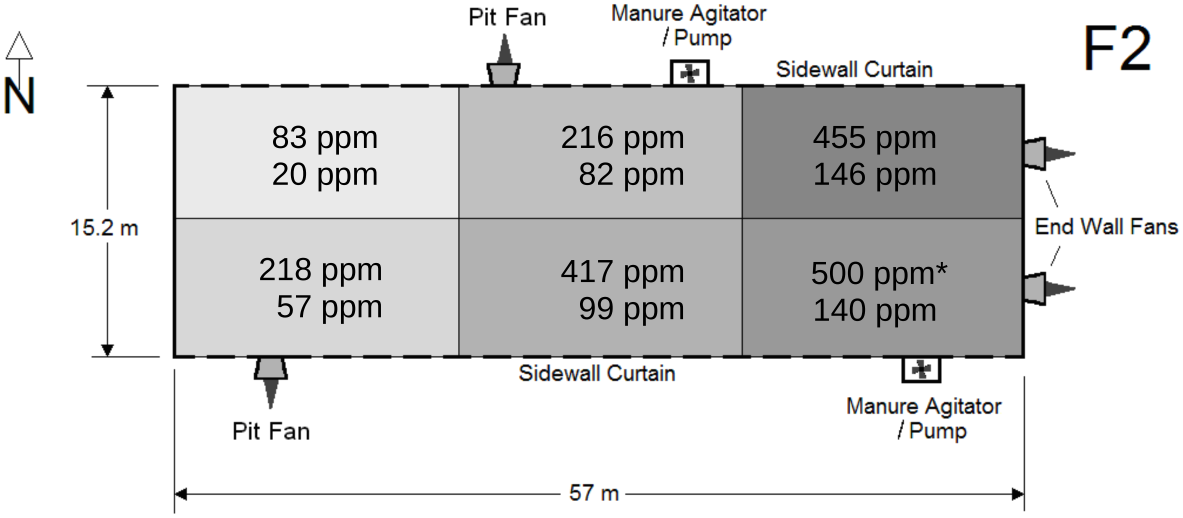
Height[†]	Location	Before Pumpout H_2S, ppm			Subsurface Agitation H_2S, ppm			Surface Agitation H_2S, ppm			After Pumpout H_2S, ppm		
		$\bar{x}$		*SE*	$\bar{x}$		*SE*	$\bar{x}$		*SE*	$\bar{x}$		*SE*
0.1	1	0.02	a	(0.02)	0.00	a	(0.53)	20.06	a	(3.01)	0.01	a	(0.61)
0.1	2	0.01	a	(0.01)	4.38	b	(0.53)	57.11	b	(3.01)	2.08	ac	(0.60)
0.1	3	0.01	a	(0.01)	10.74	d	(0.53)	81.61	c	(3.01)	6.73	e	(0.58)
0.1	4	0.01	a	(0.01)	7.96	c	(0.53)	99.23	e	(3.01)	7.18	e	(0.67)
0.1	5	0.01	a	(0.01)	7.85	c	(0.53)	145.73	f	(3.01)	5.06	deg	(0.65)
0.1	6	0.01	a	(0.01)	5.18	b	(0.53)	140.10	f	(3.01)	5.39	de	(0.65)
1.5	1	0.01	a	(0.01)	4.75	b	(0.53)	53.84	b	(3.01)	0.77	ab	(0.61)
1.5	2	0.01	a	(0.01)	4.58	b	(0.53)	54.40	b	(3.01)	3.27	cd	(0.60)
1.5	3	0.01	a	(0.01)	5.19	b	(0.53)	70.10	d	(3.01)	1.98	adf	(0.58)
1.5	4	0.01	a	(0.01)	4.24	b	(0.53)	83.97	c	(3.01)	3.34	cfg	(0.63)
1.5	5	0.01	a	(0.01)	0.00	a	(0.53)	0.01	g	(3.01)	0.01	bcf	(0.63)
1.5	6	Data unavailable due to sensor error						Data unavailable due to sensor error					
		n = 35			n = 72			n = 358			n = 40		

[†] Distance above slat floor in m

Different letters within a column indicate statistically significant difference ($P < 0.05$).



(a) Subsurface agitation



(b) Surface agitation

Figure 3.14. Spatial distribution of hydrogen sulfide in the AOZ of Finish Barn 2 according to agitation period. Color correlates to least squares means estimate for the location at animal level (darker indicates higher values). Values are the maximum (top) and least squares mean (bottom) concentration at the location for the specified time period. *Maximum detection limit of sensor.

Rapid increases in concentration can be seen in figure 3.13. This observation and the large standard deviations during aggressive surface agitation are representative of the burst characteristic of H_2S release. The barn average remains high during the pumpout, rarely returning to zero except during reduced subsurface agitation. This suggests the mixing action created by the stir fans moved hydrogen sulfide throughout the barn before it could be dispersed by exhaust ventilation.

During moderate subsurface agitation, one agitator was restricted to pumping only while the other agitated at 50% engine speed. This reduced the fluid power input to the slurry and reduced H_2S concentrations at all monitored points in the barn. Within the AOZ, locations 5 & 6 were significantly higher than all other points during aggressive surface agitation (figure 3.14b). This area experienced the highest concentrations; this is attributed to the agitation jet colliding with a support pillar. In general the locations associated with high concentrations are near agitation activity (figure 3.14).

Average and peak concentrations were higher during aggressive surface agitation with two pumps compared to moderate subsurface agitation with one pump (figure 3.14). This suggests the degree of agitation played a role in the amount of hydrogen sulfide released from manure slurry.

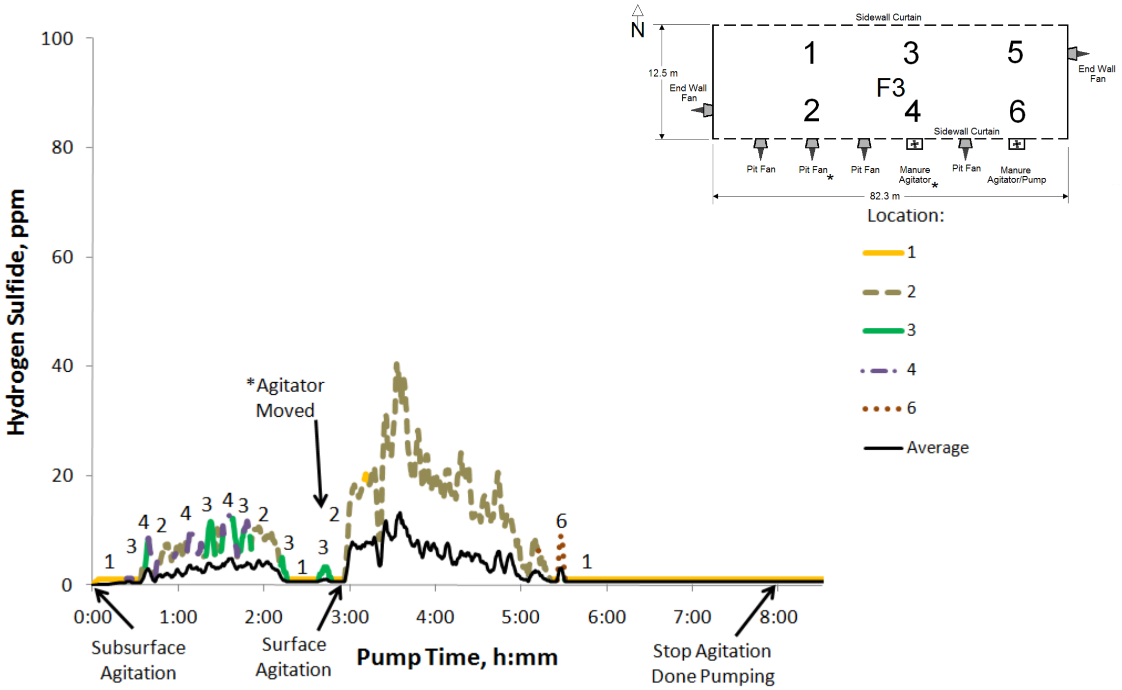
Finish Barn 3 (F3)

The location of the maximum concentration in the HOZ and AOZ throughout the pumpout event in Finish Barn 3 is illustrated in figure 3.15. In comparison to Finish Barns 1 & 2, hydrogen sulfide levels were markedly lower. The maximum concentration during this event was a short duration 61 ppm which is concealed in figure 3.15 by the three minute moving average. As a general trend, it appears the locations associated with maximum concentrations changed frequently during subsurface agitation. During moderate surface agitation maximum concentrations were primarily at location 1 & 2. This can be explained by the environment and ventilation conditions. This was caused by a north-northwest wind encountering the corner of the barn and funneling between barns. Site personnel observed no wind exiting the building at location 2; however no air velocity profile was measured.

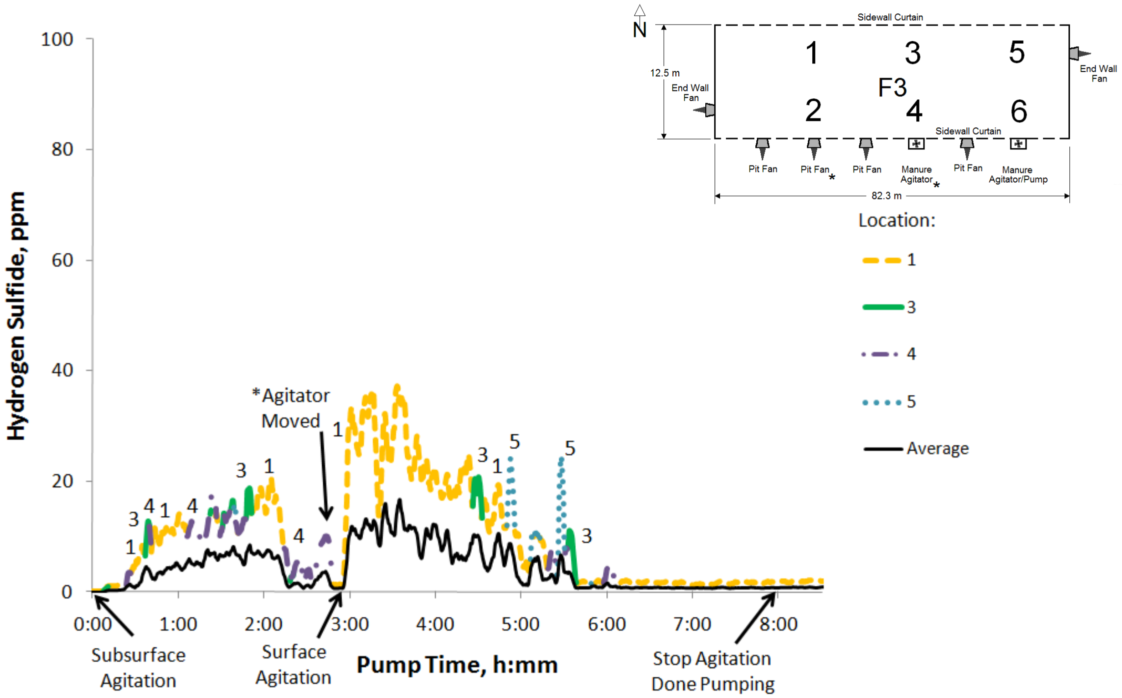
Table 3.4 shows the H_2S average concentration and standard error data for Finish Barn 3 subdivided temporally. Concentrations among monitored points within the barn were not significantly different before pumping began. The general pattern after pumping is locations 5 & 6 are significantly lower than the rest of the barn.

Concentrations increase during the pumpout event confirming agitation of manure slurry releases hydrogen sulfide, thus increasing in-barn concentrations and emissions. Furthermore, significant interaction existed between all fixed effects during all subdivided time periods, suggesting hydrogen sulfide spatial variation is complex and varies considerably with respect to space. Again, rapid increases in concentration occurred, exemplifying the burst characteristic.

During surface agitation, one agitator was continuously agitating near location 2. Concentrations in the AOZ at location 1 were significantly higher than all other monitored points within the barn (figure 3.16).



(a) Human occupied zone



(b) Animal occupied zone

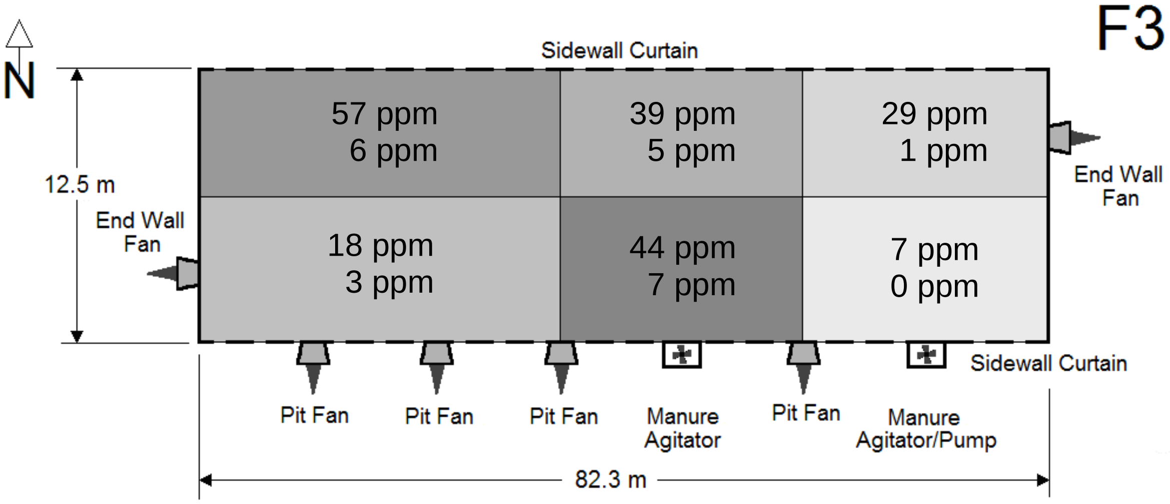
Figure 3.15. Maximum concentrations corresponding to location and zone within Finish Barn 3. Color and number indicate location within the barn.

Table 3.4. Average and standard error of the mean hydrogen sulfide concentration at each monitored location in Finish Barn 3 subdivided temporally.

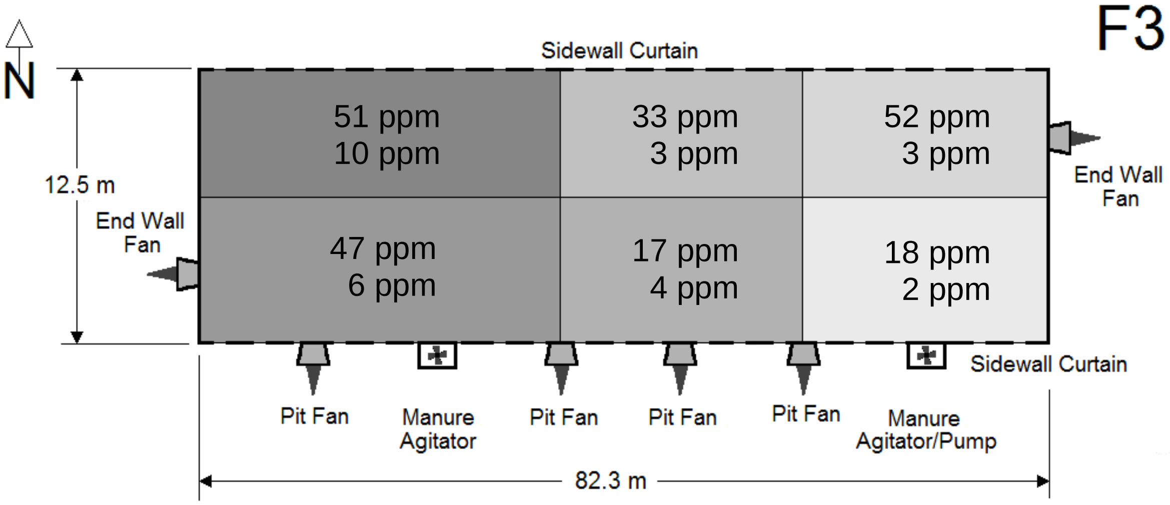
Height†	Location	Before Pumpout			Subsurface Agitation			Surface Agitation			After Pumpout		
		H_2S, ppm			H_2S, ppm			H_2S, ppm			H_2S, ppm		
		$\bar{x}$		*SE*	$\bar{x}$		*SE*	$\bar{x}$		*SE*	$\bar{x}$		*SE*
0.1	1	0.01	a	(0.01)	6.32	a	(0.22)	10.05	a	(0.25)	1.35	a	(0.02)
0.1	2	0.01	a	(0.01)	3.35	c	(0.22)	6.01	c	(0.25)	0.56	c	(0.02)
0.1	3	0.01	a	(0.01)	5.08	d	(0.22)	3.07	e	(0.25)	1.00	b	(0.02)
0.1	4	0.01	a	(0.01)	7.18	a	(0.22)	3.74	e	(0.25)	0.52	d	(0.02)
0.1	5	0.01	a	(0.01)	1.34	b	(0.22)	2.91	e	(0.25)	0.17	e	(0.02)
0.1	6	0.01	a	(0.01)	0.08	e	(0.22)	1.78	f	(0.25)	0.01	f	(0.02)
1.5	1	0.07	b	(0.01)	1.97	b	(0.22)	4.88	b	(0.25)	0.99	b	(0.02)
1.5	2	0.01	a	(0.01)	3.33	c	(0.22)	8.47	d	(0.25)	0.99	b	(0.02)
1.5	3	0.01	a	(0.01)	3.10	c	(0.22)	1.46	f	(0.25)	0.54	cd	(0.02)
1.5	4	0.01	a	(0.01)	3.47	c	(0.22)	1.34	f	(0.25)	1.00	b	(0.02)
1.5	5	0.01	a	(0.01)	0.05	e	(0.22)	0.63	f	(0.25)	0.01	f	(0.02)
1.5	6	0.01	a	(0.01)	0.09	e	(0.22)	1.54	f	(0.25)	0.02	f	(0.02)
		n = 46			n = 332			n = 608			n = 407		

† Distance above slat floor in m

Different letters within a column indicate statistically significant difference ($P < 0.05$).



(a) Subsurface agitation



(b) Surface agitation

Figure 3.16. Spatial distribution of hydrogen sulfide in the AOZ of Finish Barn 3 according to agitation period. Color correlates to least squares means estimate for the location at animal level (darker indicates higher values). Values are the maximum (top) and least squares mean (bottom) concentration at the location for the specified time period. *Maximum detection limit of sensor.

Sow Barn 1 (S1)

The location of the maximum concentration in Sow Barn 1 before, during, and after the pumpout event is illustrated in figure 3.17. The hydrogen sulfide levels were clearly lower when compared to all finish barn pumpouts. No method to agitate slurry within the pit was employed at this barn. The manure was strictly pumped from the pit and supplied to a drag hose for injection into the soil. This indicates that to prevent H_2S release during pumpouts, no agitation should be performed.

The maximum concentration for the entire monitored period was 1.2 ppm. This occurred briefly when personnel first entered the barn to adjust ventilation and check the monitoring system prior to the pumpout beginning. The maximum concentration during the pumpout was 0.8 ppm. The sample collected from the pit headspace was the location of maximum concentration for the majority of the monitored period. As expected, hydrogen sulfide concentrations after the pumpout were less than before the pumpout because the manure containing the H_2S had been removed.

Hydrogen sulfide concentration data for Sow Barn 1 subdivided temporally is listed in table 3.5. Concentrations among monitored points within the barn were significantly different before and during the pumpout. After the pumpout high manual ventilation was maintained until swine workers returned in the morning. Concentrations remained less than 0.3 ppm during the work day following the pumpout.

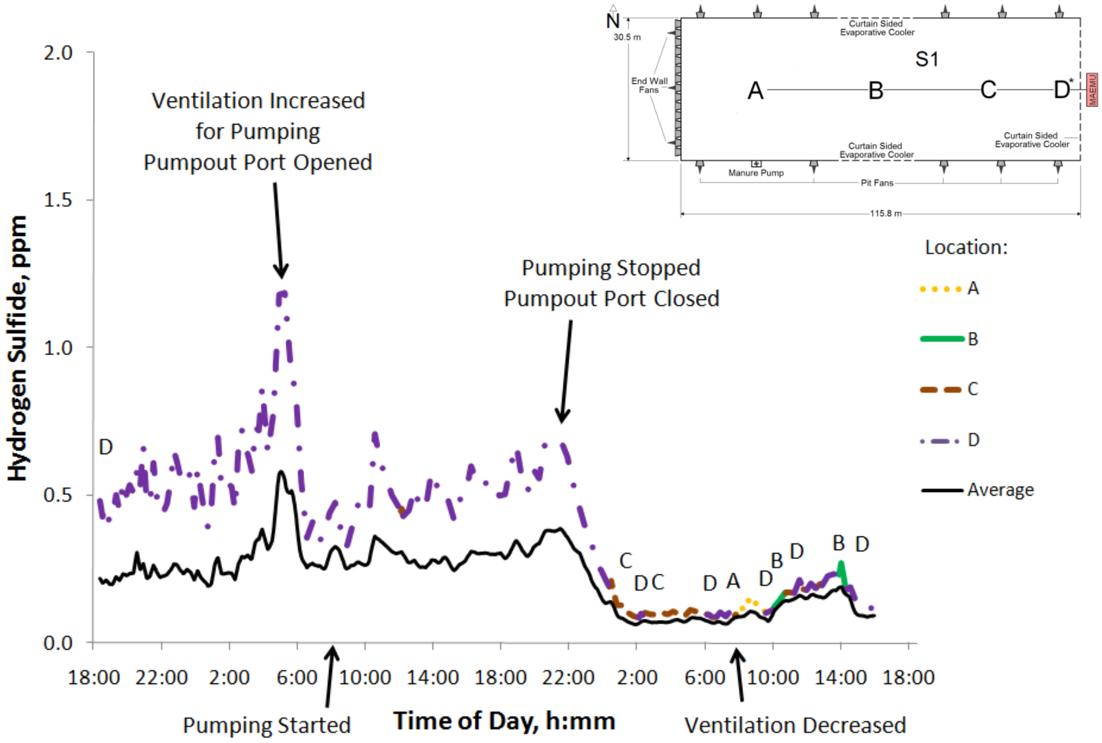


Figure 3.17. Graph of maximum concentration corresponding to location within Sow Barn 1. *Location D is in the pit headspace.

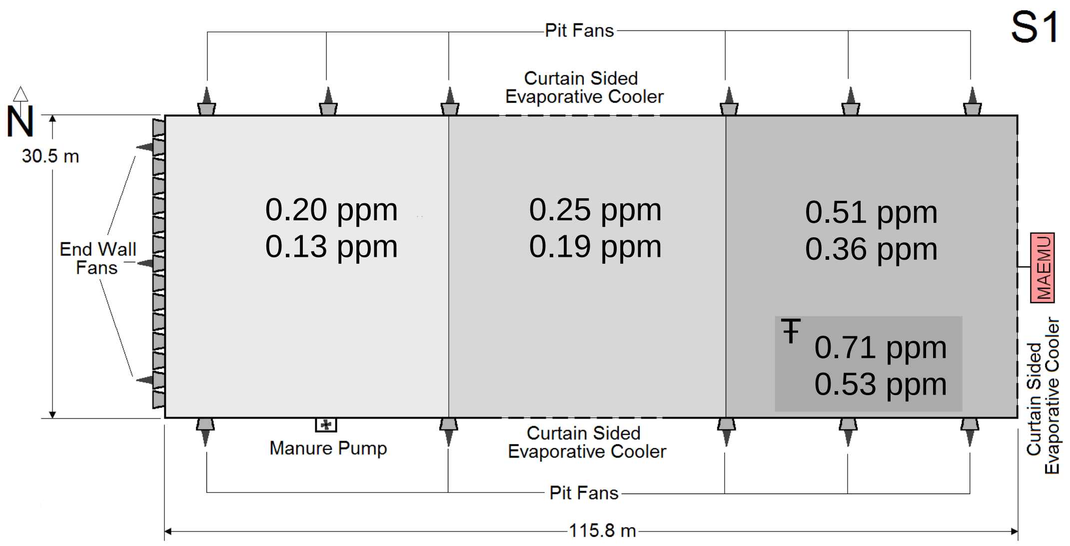


Figure 3.18. Spatial distribution of hydrogen sulfide in Sow Barn 1 during the manure pumpout. Color correlates to least squares means estimate for the location at animal level (darker indicates higher values). Values are the maximum (top) and least squares mean (bottom) concentration at the location for the specified time period. Ŧ Indicates pit headspace location.

Table 3.5. Average and standard error of the mean hydrogen sulfide concentration at each monitored location in Sow Barn 1 subdivided temporally.

Height[†]	Location	Before Pumpout			During Pumpout			After Pumpout High Ventilation			After Pumpout Auto Ventilation		
		H_2S, ppm			H_2S, ppm			H_2S, ppm			H_2S, ppm		
		$\bar{x}$		*SE*	$\bar{x}$		*SE*	$\bar{x}$		*SE*	$\bar{x}$		*SE*
1.5	A	0.14	a	(0.01)	0.13	a	(0.01)	0.04	a	(0.01)	0.11	a	(0.01)
1.5	B	0.12	b	(0.01)	0.19	b	(0.01)	0.07	b	(0.01)	0.12	b	(0.01)
1.5	C	0.29	c	(0.01)	0.36	c	(0.01)	0.11	c	(0.01)	0.13	b	(0.01)
-0.1	D	0.58	d	(0.01)	0.53	d	(0.01)	0.11	c	(0.01)	0.15	c	(0.01)
		n = 867			n = 881			n = 509			n = 479		

[†] Distance above slat floor in m

Different letters within a column indicate statistically significant difference ($P < 0.05$).

Manure Nutrient Analysis

Table 3.6 lists the results of manure nutrient analysis for all monitored barns. The manure in the gestation sow barn (S1) was very dilute in comparison to the finish barns. It had the lowest levels of sulfur and solids content, as well as the highest pH of all barns in the study. A previous laboratory scale study by Arogo et al. (2000) concluded that manure with more solids and lower pH resulted in higher H_2S production. Although the sulfur content of the manure in the finish barns is similar, solids content of manures in F1 and F2 is double that of F3. Hydrogen sulfide concentration in the monitored barns agrees with the H_2S production conclusion of Arogo et al. (2000).

Table 3.6. Manure nutrient analyses for all monitored barns.

Barn	**F1**	**F2**	**F3**	**S1**
NH_4^+-N, %	0.41	0.41	0.40	0.15
Organic N, %	0.15	0.15	0.24	0.01
TN, %	0.56	0.56	0.64	0.16
P_2O5, %	0.42	0.42	0.29	0.06
K_2O, %	0.44	0.44	0.40	0.11
S, %	0.09	0.09	0.08	0.01
Ca, %	0.17	0.17	0.12	0.03
Mg, %	0.13	0.13	0.09	0.01
Na, %	0.09	0.09	0.08	0.03
Cu, ppm	44	44	21	1
Fe, ppm	146	146	102	27
Mn, ppm	37	37	25	4
Zn, ppm	173	173	11	11
Solids, %	10.4	10.4	5.6	0.8
pH	8.0	8.0	8.1	8.2

Conclusions

The hydrogen sulfide conditions within the barns in this study varied based on manure slurry agitation, degree of agitation, and wind and ventilation conditions. Significant interaction existed between all fixed effects during all subdivided time periods suggesting hydrogen sulfide spatial distribution is complex. Statistical analysis resulted in no linear correlation among locations and heights within the individual barns included in this study.

Concentrations reached the maximum detection limit, 500 ppm H_2S, where the agitation jet collided with a support pillar in barns F1 and F2. Of all barns monitored, these are the only locations to reach the maximum range of the sensor. Slurry within F1 and F2 was agitated very aggressively since no swine were present, while the manure in Barn F3 was moderately mixed. Furthermore, one pump operated at reduced engine speed with the agitation nozzle below the slurry surface in Barn F2 resulted in the lowest maximum H_2S concentrations of all barns monitored during agitation. This implies the degree of agitation is key to managing in-barn hydrogen sulfide during manure pumpouts.

The highest peak concentrations occurred during the first agitation period of the manure pumpout. In barns F1 and F3 this was during subsurface agitation, F2 was during surface agitation. The minimum concentration in all finish barns was less than one ppm, the lowest detection limit of the sensor network. This suggests the greatest potential for high concentrations is early during agitation.

The lowest H_2S concentrations of all barns monitored in this study were within the gestation barn (S1). Hydrogen sulfide concentrations remained below 1 ppm in the gestation barn (S1) during manure pumpout. This is due to the lack of agitation to mix the slurry within the pit. This demonstrates in-barn H_2S risks can be minimized with no agitation.

This study confirms the hypothesis that high H_2S concentrations occur localized to the agitation source or suspected areas of unfavorable airflow patterns that allow accumulation of H_2S. The concentrations in these areas can reach lethal conditions. This is concurrent with the report from custom manure applicators that swine loss occurs near the agitation source or areas suspected to be inadequate in ventilation.

The following recommendations are suggested based on the results of this study:

1. Never allow any person inside a barn during manure slurry pumpouts with agitation.
2. If using a hydrogen sulfide detection system, monitor locations near agitation activity and areas suspected deficient in ventilation.
3. Do not agitate manure slurry during manure pumpouts to minimize risks associated with in-barn H_2S. If agitation is used, reduce the duration and aggressiveness of agitation. Avoid abruptly initiating agitation; instead, gradually increase power to the pump for agitation.
4. Avoid directing the agitation jet toward obstructions.

Future Research

Further research in controlled replicated experiments is recommended to confirm the spatial distribution with greater statistical power. During this experiment multiple barn designs were pumped using different strategies which hindered true replication. Future research would ideally monitor multiple barns located on the same site, pumped with the same manure application equipment, and many sites monitored. Thus a larger number of barns would be monitored, accounting for the variability between barns. Manure pumping protocol (nozzle orientation, degree of agitation, ventilation management) should be similar for all barns monitored. Furthermore lab scale experiments are recommended to determine a correlation between fluid energy for agitation and hydrogen sulfide release. It is suspected the energy and hydrogen sulfide release are directly related.

Acknowledgements

This project is funded by a grant from the National Pork Board and the Iowa Pork Producers Association.

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CHAPTER 4. ASSESSMENT OF HYDROGEN SULFIDE EXPOSURE IN DEEP-PIT SWINE HOUSING

To be submitted to *Journal of Agricultural Safety and Health* for publication

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Abstract

The objective of this paper is to assess in-barn hydrogen sulfide (H_2S) conditions by comparing measured concentrations to American Conference of Governmental Industrial Hygienists (ACGIH) and National Institute for Occupational Safety and Health (NIOSH) exposure levels during normal operation and manure removal and agitation periods for finish swine and gestation sow barns. In-barn monitoring was performed in three finish swine and one gestation sow barn during manure removal events in the fall of 2009. Two finish swine barns were monitored continuously from November 2009 to April 2010. One gestation sow barn was monitored for three days in addition to one manure removal event. Aggressive agitation can quickly generate very high in-barn H_2S concentrations. Results from this study suggest H_2S was not an exposure hazard to workers and swine during normal operation periods in all barns monitored. However, exposure to H_2S exceeds short term exposure limits and ceiling concentrations in swine barns during manure removal events with agitation. In some instances, concentrations exceeded immediately dangerous to life and health and the lethal concentration to 50% of the population (LC_{50}) dosage.

Introduction

Human Exposure

During the period of 1983-1990, H_2S poisoning was responsible for the death of 24 swine workers in the Midwest alone and at least 15 more deaths since 1994 (Wallinga, 2004). Dangerous H_2S concentrations for humans vary, but one source sets the levels at 500 ppm for unconsciousness and 600 ppm for immediate death (Wallinga, 2004). Other sources have set the level for immediate death as high as 1,000 ppm; however, the level set by the National Institute for Occupational Safety and Health (NIOSH) for immediate danger is 100 ppm. A previous study by Chénard et al. (2002) indicated that H_2S levels can meet or exceed the American Conference of Governmental Industrial Hygienists (ACGIH) standards for H_2S Threshold Limit Values Short Term Exposure level (TLV-STEL) during normal operation daily tasks in a swine house with shallow pit storage. In that study, point measurements were taken at in-house locations thought to be traveled by swine workers, but no sensor grid was used to describe H_2S distribution in the barn.

The ACGIH and NIOSH devise recommendations or threshold limit values (TLV) for safe exposure to chemicals and other hazards. A worker should not have adverse health effects when exposed to a concentration equal or lower to the specific time weighted average, TLV-TWA, assuming exposure of 8 hours per day for a maximum of 40 hours per week. In certain circumstances workers must be exposed to a higher concentration than the TLV-TWA for a short duration. ACGIH guidelines include the TLV-STEL, a concentration to which workers may be exposed to, for a period of 15 minutes only, four times a day, separated by at least 1 hour between exposures. Two other exposure guidelines are a ceiling concentration (TLV-CEIL), a concentration which should not be exceeded regardless of exposure duration. The Immediately Dangerous to Life or Health (IDLH) guideline by NIOSH is a concentration that is likely to cause immediate or permanent negative health effects or prevent escape from the environment. Lethal concentration to 50% of the population (LC_{50}) values range from 444 – 800 ppm based on toxicity tests. A summary of the exposure guidelines is shown in table 4.1. These exposure guidelines have been adopted by the United States Occupational Safety and Health Administration (OSHA) as standards for exposure. However OSHA's limits for air contaminants are not applicable to agricultural operations, based on 29 CFR 1928.21(b) of the Federal Register.

Table 4.1. Guidelines for exposure to hydrogen sulfide.

	TLV-TWA	**TLV-STEL**	**TLV-CEIL**	**IDLH**	**LC_{50}**
Concentration, ppm	10	15	20	100	444
Concentration, mg/m^3	14	21	28	140	622

Animal Exposure

Previous research by Patni and Clarke (2003) noted that during pit agitation, the burst characteristic of H_2S gas release makes it hazardous. This and other studies have shown that H_2S levels can go from harmless to lethal in minutes during agitation or mixing of manure in sub-floor pits. However, a study by Robert et al. (2001) states that increased ventilation can effectively clear H_2S from a swine house. It is not common practice for swine to be removed from a barn prior to manure removal. The resources required to temporarily move an entire barn of swine is infeasible for livestock production. Since manure removal can usually be performed in a day, it is common for ventilation to be increased to clear potential H_2S bursts that may occur during the manure removal process.

Puck Custom Enterprises (PCE) is a custom slurry removal and application business located in western Iowa. In the past, PCE has seen an average of 20-30 swine/year succumb to H_2S poisoning associated with slurry agitation. In all cases preventive measures were employed to avoid the loss of animal life. Ventilation was increased and no personnel were allowed in the swine barn during manure removal yet these swine losses still occurred. The worst event PCE experienced occurred in January of 2006 when 300 swine ready for market died from H_2S poisoning in a single barn (Puck, 2006). In this instance the same preventative measures were taken as the previous 5 years at that barn, when no swine loss occurred. This demonstrates the unpredictability in-barn high concentration H_2S environments during manure removal.

Swestka et al. (2010) collected hydrogen sulfide concentration data from multiple locations in deep-pit finish swine and gestation sow barns to determine spatial distribution. This data can be further processed to analyze exposure potential to swine and swine workers. The objective of this paper is to assess in-barn hydrogen sulfide (H_2S) conditions by comparing measured concentrations to American Conference of Governmental Industrial Hygienists (ACGIH) and National Institute for Occupational Safety and Health (NIOSH) exposure levels during normal operation and manure removal and agitation periods for finish swine and gestation sow barns.

Materials and Methods

Description of the Monitoring Equipment

Two monitoring systems were utilized to monitor the interior environment of multiple swine barns. Both systems monitored ambient hydrogen sulfide concentrations within a swine barn. A low concentration system, less than 20 ppm, monitored deep-pit finish swine and sow gestation barns during normal operation and non-agitation manure removal events. A high concentration system, maximum 500 ppm, monitored deep-pit finish swine barns during manure removal events with agitation.

Low Concentration Hydrogen Sulfide Measurement System

A Teledyne API Model 101E H_2S analyzer (figure 4.1) was used to measure H_2S within air samples collected from the subject swine barns. The analyzer has a user-programmable maximum range of 50-20,000 ppb and the option to use ppb or ppm units. The maximum range, 20 ppm, was selected due to the potential for H_2S bursts during manure slurry removal events. The unit was calibrated prior to use with 20 ppm H_2S cylinder gas (Matheson Tri-Gas, Inc., Montgomeryville, PA).

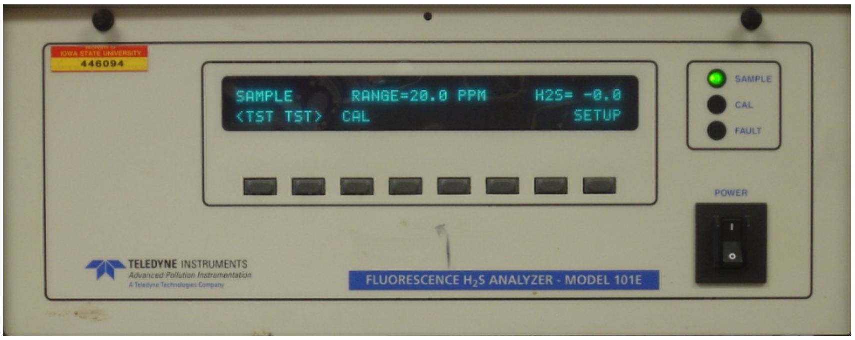


Figure 4.1. A Teledyne API Model 101E H_2S analyzer located inside the MAEMU measured H_2S concentrations of air inside the swine barn.

Data acquisition was accomplished with a National Instruments Compact Field Point and LabView program logging the analyzer output every second.

A Mobile Air Emissions Monitoring Unit (MAEMU) previously designed by project personnel to monitor emissions from broiler facilities (Moody et al., 2008) collected air samples from the subject swine barns. Teflon tubing (Fluorotherm FEP tubing) was routed from the sample location within the barn to the MAEMU and connected to an individual supply pump. Each pump supplied air to a circuit of solenoids which opened or closed to rotate samples on a programmed interval controlled by a computer. Air from one sample location was allowed to pass to the analyzer at a time to prevent sample contamination. The tubing was heated from the MAEMU to the barn interior to prevent condensation of the sample air. A paper filter inside the barn prevented dust from plugging the tubing and a Teflon filter inside the MAEMU prevented fine dust from damaging the H_2S analyzer.

High Concentration Hydrogen Sulfide Measurement System

A wireless sensor network of electrochemical H_2S sensors developed by Swestka et al. (2010) was used to monitor high concentration H_2S. The Pem-Tech Model PT295 HEC H_2S (Pem-Tech Inc., Sugar Land, TX) is a passive sensor which monitors the ambient air near the sensor. This sensor is primarily used in the oil and petrochemical industry but has demonstrated to be within five percent of a H_2S analyzer during swine slurry agitation and removal events (Muhlbauer et al., 2008). Each sensor transmitted readings every 30 seconds to a receiver connected to a computer located outside the swine barn. The data from the wireless sensor network was grouped into a 30 second window to represent a “snapshot” of the H_2S concentrations in the barn.

A total of 12 H_2S sensor units (figure 4.2) were constructed to be supported from the ceiling or overhead automatic feed delivery system and monitor two heights (1.5 m and 0.1 m) at six locations within the barn. These heights were selected to represent the human breathing zone (1.5 m above the slat floor) and the pig breathing zone (0.1 m above the slat floor).

Figure 4.2. Hydrogen sulfide wireless sensor units measured high concentration hydrogen sulfide within the swine barn during manure removal and agitation events.

Site Description

Three deep-pit swine finish and one deep-pit sow gestation barns located in Iowa were monitored during manure removal events in fall 2009. The high concentration hydrogen sulfide measurement system was used in the swine finish barns. Furthermore, two deep-pit swine finish barns were monitored continuously for five months with the low concentration hydrogen sulfide measurement system. The deep-pit sow gestation barn was sporadically monitored for four days including one slurry removal event with the low concentration H_2S system. Data summarizing the barn characteristics is provided in table 4.2.

Data Analysis

Daily normal operation data for each barn was first ranked by highest peak concentration. For the finish barn data, the top twenty days were analyzed for time weighted average exposure assuming a worker was present in the environment for eight hours or swine present for 24 hours. A time weighted average was calculated for each sample location within the barn by multiplying the concentration (C) and the time duration (T), shown in equation 4.1. Regardless of the actual duration of exposure, the calculated TWA must be normalized to an eight hour duration because the guidelines are based on an eight hour exposure period. The same procedure was followed for the normal operation sow barn data, however time weighted average was calculated for all data.

Equation 4.1

$$TWA = \frac{C_1 \bullet T_1 + C_2 \bullet T_2 + \Lambda \ + C_n \bullet T_n}{8hr}$$

Data from manure removal events was analyzed for time weighted average using equation 4.1. For worker exposure, the exposure duration was assumed to be the duration of the manure removal event or eight hours, whichever was shorter. For swine exposure, the exposure duration was assumed to be the duration of the manure removal event. Furthermore, the data was analyzed for compliance with TLV-STEL, IDLH, and LC_{50} guidelines.

Table 4.2. Characteristics of barns monitored for this research.

Barn	**F1**	**F2**	**F3**	**S1**
Animal type	Finish swine	Finish swine	Finish swine	Gestation sows
Animal capacity	1,250	1,250	1,500	1,800
Room area	866 m^2	866 m^2	1,029 m^2	3,532 m^2
Ventilation method	Natural and mechanical	Natural and mechanical	Natural and mechanical	Mechanical
Manure handling method	Sub-floor deep-pit storage	Sub-floor deep-pit storage	Sub-floor deep-pit storage	Sub-floor deep-pit storage
Manure removal frequency	1-2 times per year	1-2 times per year	1-2 times per year	1-2 times per year
Manure removal method	Pump with recirculation agitation	Pump with recirculation agitation	Pump with recirculation agitation	Pump only no agitation
Manure removal duration[†]	5:23	3:45	8:00	14:50
Workers present during manure removal	No	No	No	Yes, limited duration

[†] Time in hh:mm

Results and Discussion

Normal Operation

Hydrogen sulfide concentrations, during normal operation periods, remained far below the exposure guidelines. Table 4.3 summarizes the exposure assessment results for human and swine during normal operation periods. The peak or highest concentration recorded during normal operation of all barns was 2.1 ppm in barn F2. This was recorded during the period with the highest human exposure TWA, 1.8 ppm, of all barns during normal operation. Continuous exposure to the H_2S is also below the exposure guidelines. The highest TWA for swine exposure was 4.9 ppm in barn F2. These concentrations and TWA values occurred during the winter when barn ventilation is at a minimum to prevent heat loss. Human and swine exposure did not exceed any exposure guidelines for the monitored periods inside the barns included in this study.

Table 4.3. Exposure assessment of deep-pit swine barns monitored during normal operation.

		Human Exposure			Swine Exposure		
	Barn	**F1**	**F2**	**S1**	**F1**	**F2**	**S1**
	Peak Concentration H_2S, ppm	1.7	2.1	1.2	1.7	2.1	1.2
	Exposure Duration †	8:00	8:00	8:00	24:00	24:00	24:00
	TWA, ppm *	1.2	1.8	0.9	3.4	4.9	2.1
Exposure Guideline Exceeded	TLV-TWA	NO	NO	NO	NO	NO	NO
	TLV-STEL	NO	NO	NO	NO	NO	NO
	TLV-CEIL	NO	NO	NO	NO	NO	NO
	IDLH	NO	NO	NO	NO	NO	NO
	LC_{50}	NO	NO	NO	NO	NO	NO

† Time in hh:mm

*Based on indicated exposure duration

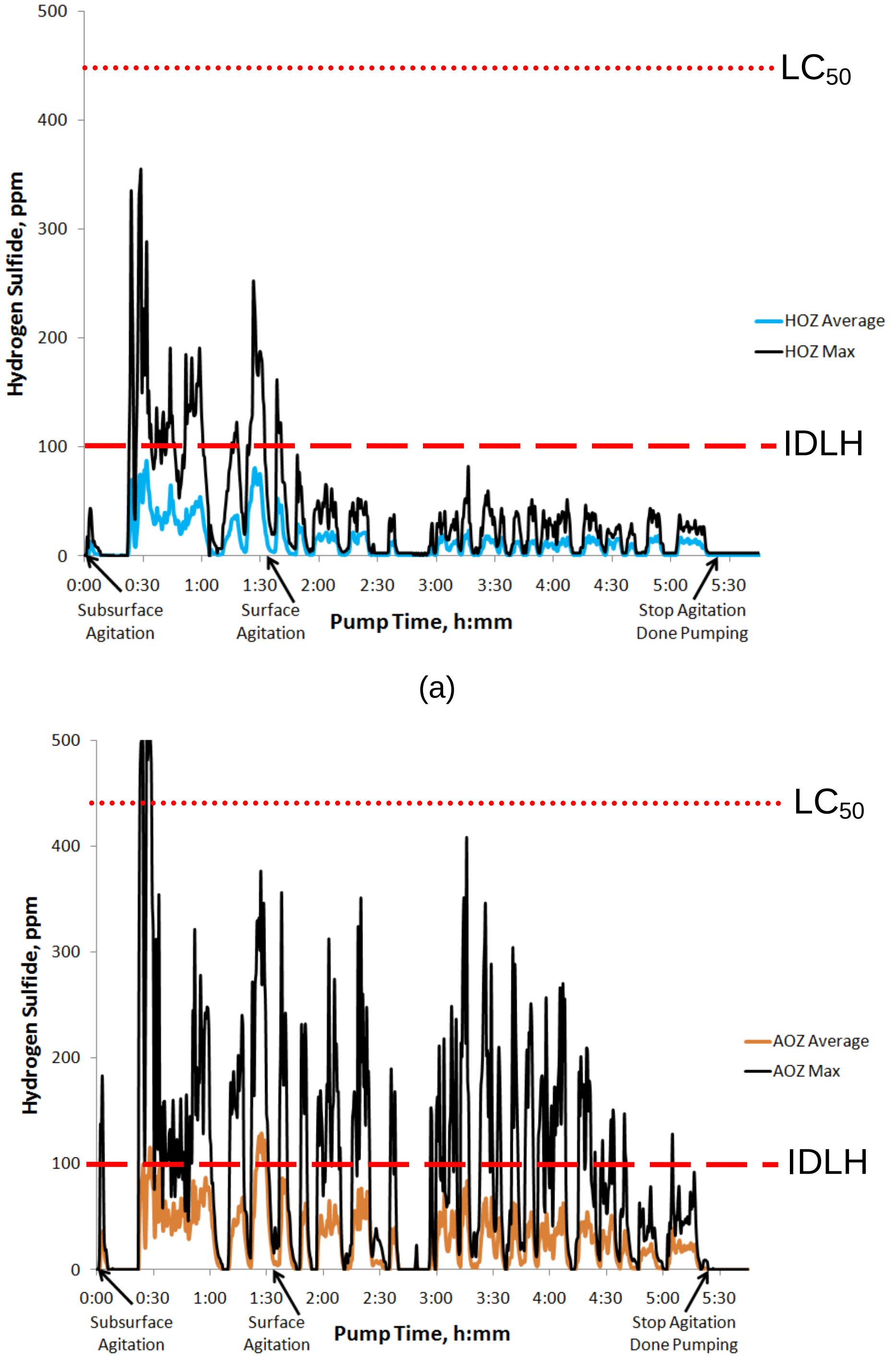
Manure Removal Events

Figures 4.3, 4.4, and 4.5 from Swestka et al. (2010) illustrate the average concentration and range of H_2S in the human and pig zones for three deep-pit swine finish barns. In observing the figures it is quickly noticed that concentrations change rapidly throughout the event. A three minute moving average was applied to the data to better illustrate this dynamic cyclical change during agitation (figure 4.6) (Swestka et al., 2010). The dynamic changes in concentration were attributed to the cycling action of turning agitation on and off to fill application tanks and agitate manure slurry in the pit during surface and subsurface agitation.

The highest concentration recorded, 500 ppm in finish barns 1 and 2, shown in figures 4.3 and 4.4 respectively, exceeded the LC_{50} guideline. The LC_{50} guideline was exceeded for five and eight minutes in finish barns 1 and 2, respectively. This is the upper detection limit of the high concentration H_2S measurement system. The actual concentration could have been higher. Even with increased ventilation the environment within these barns was potentially lethal to humans and swine. However during these events no swine were present and workers were not allowed to enter. Since swine were not present very aggressive agitation was used to mix the slurry for land application. The slurry applicators acknowledged had swine been present agitation would have been much less aggressive. Had swine or workers been present in barns F1 and F2, overexposure according to all exposure guidelines would have occurred.

Swine were present during the manure removal event in barn F3, thus agitation was much less aggressive in comparison to barns F1 and F2. The highest concentration recorded, 61 ppm, exceeded TLV-CEIL guidelines (figure 4.4). According to the TLV-CEIL and TLV-STEL guidelines, swine in barn F3 were overexposed to hydrogen sulfide. However, the maximum TWA for an individual monitored location was within guidelines, indicating when bursts did not occur H_2S levels were 10 ppm or less. No workers were allowed to enter the barn during manure removal and no swine were lost during this event.

Exposure guidelines were not exceeded for human or swine during the manure removal event in barn S1. As shown in figure 4.7, the highest concentration recorded during the event was 0.7 ppm and 1.2 ppm before the event; these levels are far below the TLV-CEIL guideline. Furthermore, the TLV-TWA for swine being continuously exposed to the environment was well below TLV-TWA guidelines. In comparison to the concentrations in the finish barns during manure removal, the hydrogen sulfide levels were dramatically lower. This suggests hydrogen sulfide concentrations can be maintained below the 10 ppm TLV-TWA guideline during manure removal events by not agitating manure slurry.



(a)

(b)

Figure 4.3. Average and maximum concentrations within the human (a) and animal (b) occupied zones for Finish Barn 1. Adapted from Swestka et al. (2010).

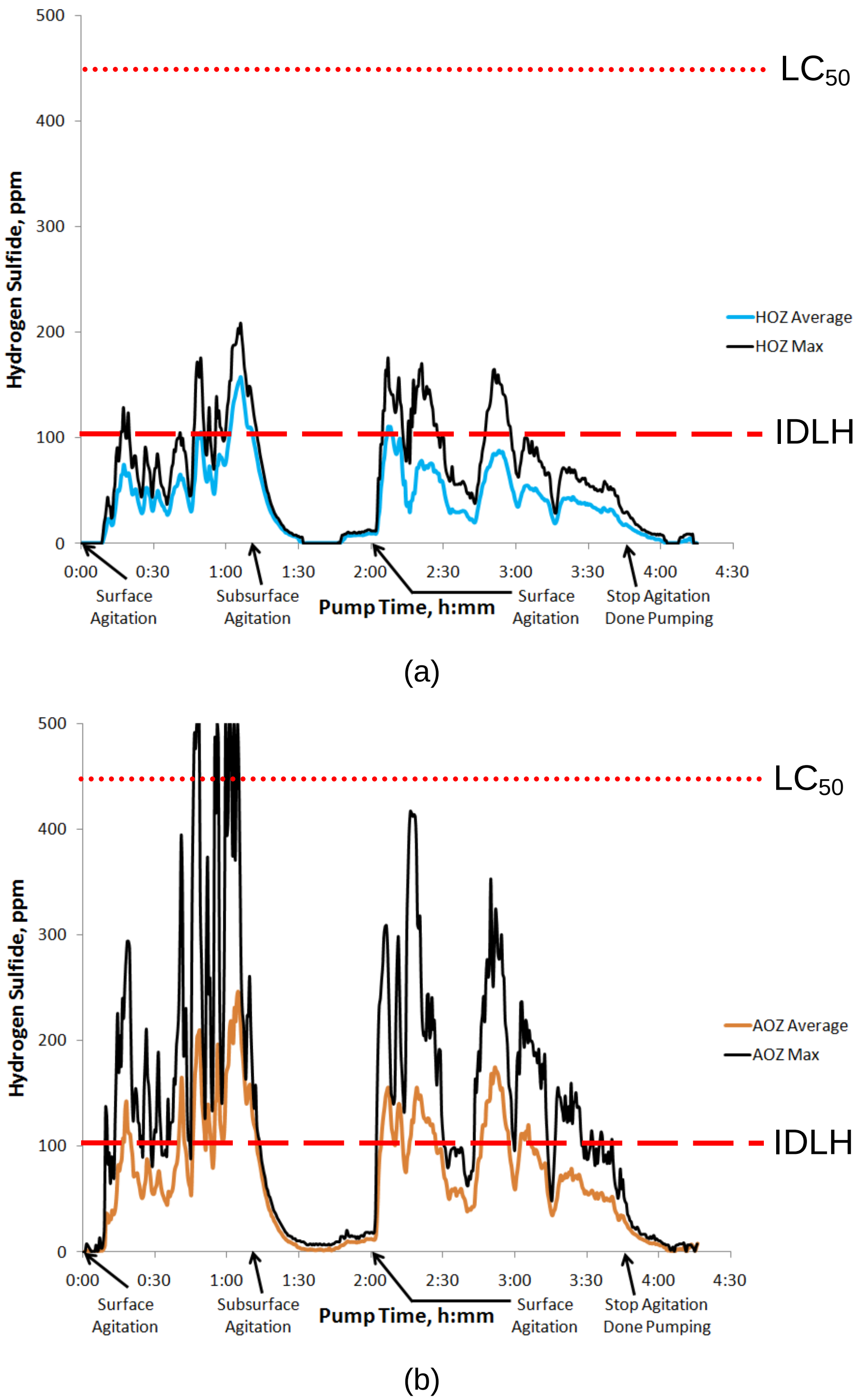
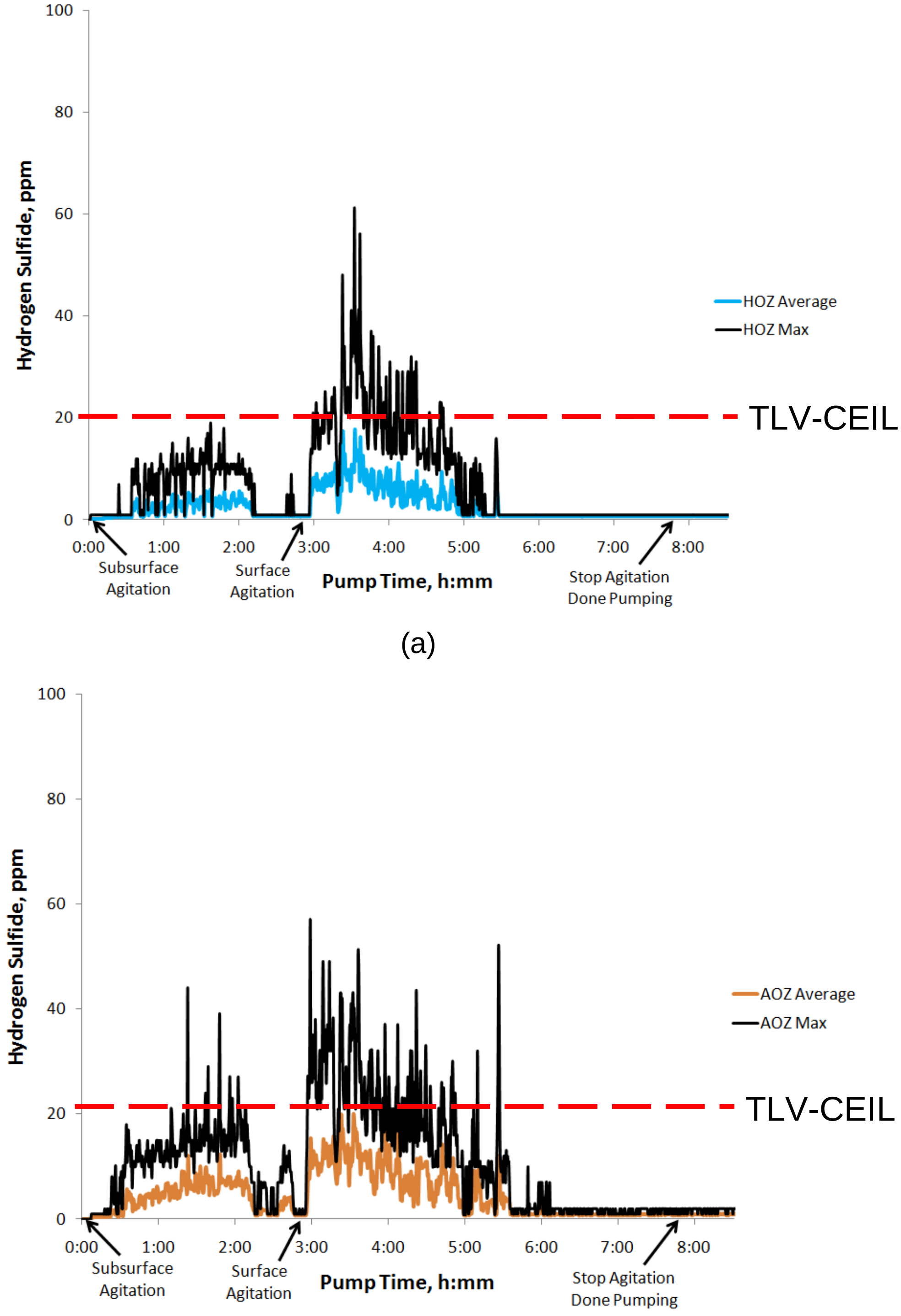


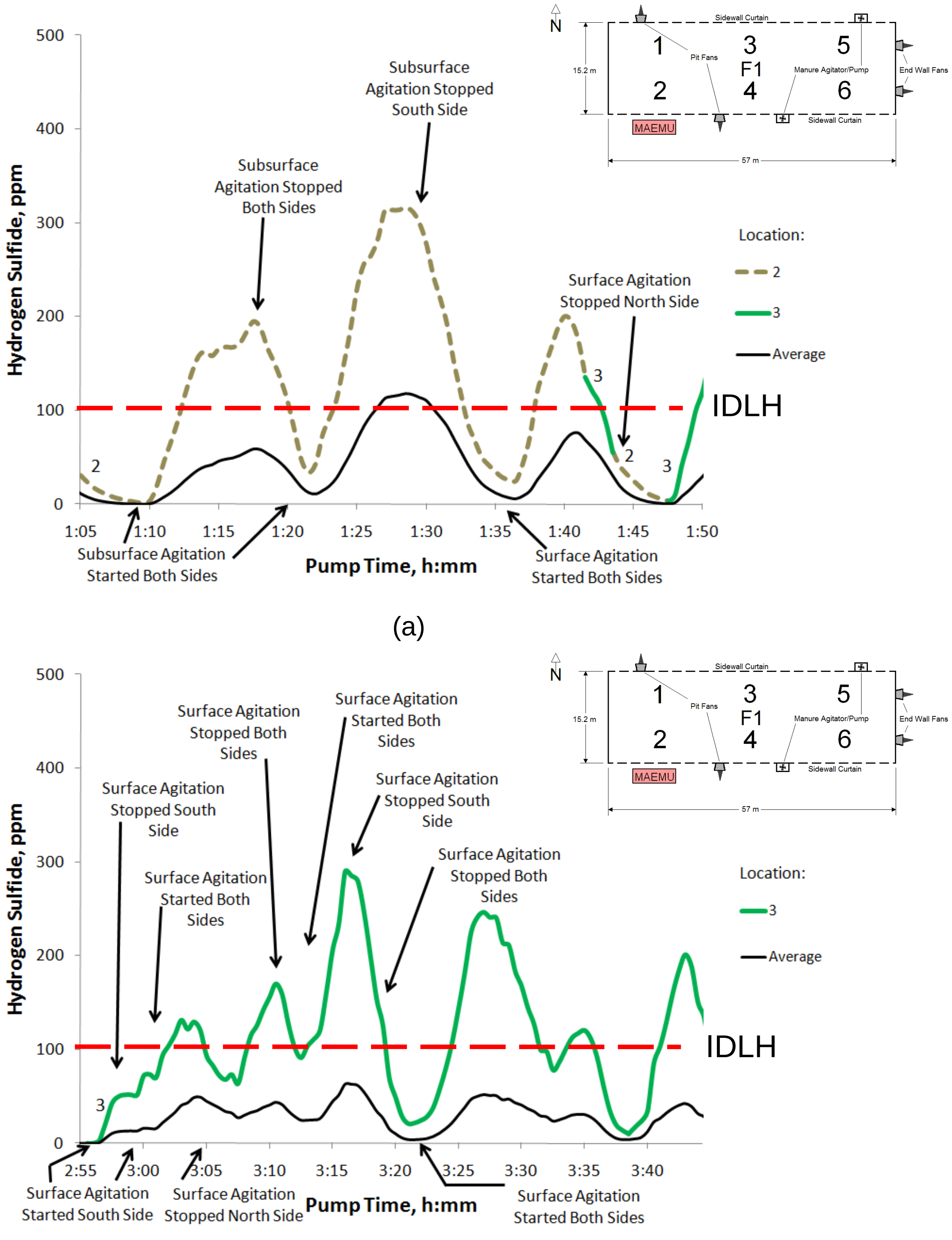
Figure 4.4. Average and maximum concentrations within the human (a) and animal (b) occupied zones for Finish Barn 2. Adapted from Swestka et al. (2010).



(a)

(b)

Figure 4.5. Average and maximum concentrations within the human (a) and animal (b) occupied zones for Finish Barn 3. Adapted from Swestka et al. (2010)



(a)

(b)

Figure 4.6. H_2S levels react to agitation activity, increasing and decreasing as agitation starts and stops during subsurface (a) and surface (b) agitation. AOZ data from Finish Barn 1. Adapted from Swestka et al. (2010).

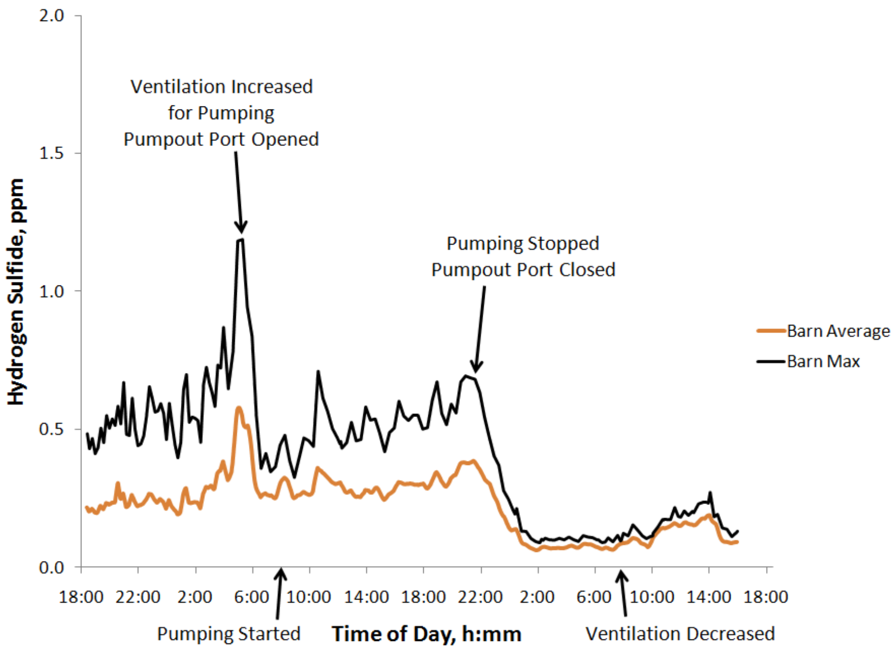


Figure 4.7. Average and maximum concentrations within the sow barn. Adapted from Swestka et al. (2010).

In general, concentrations were lower in the human zone than the animal zone for each barn. This suggests that H_2S concentrations are greater closer to the manure slurry surface. Also, as the pumpout event neared completion H_2S releases decreased in concentration. This suggests H_2S has been driven out of the slurry by agitation and as the event continues releases decrease. Furthermore, the risk for high concentration H_2S bursts is greatest at the beginning of the event before H_2S has been released out of the slurry. Concentrations during manure removal events varied between barns. These variations are attributed to manure agitation, degree of agitation, and potential differences in manure composition. Table 4.4 summarizes the exposure assessment results during manure removal events.

Table 4.4. Exposure assessment of deep-pit swine barns monitored during manure removal.

	Barn	**F1**	**F2**	**F3**	**S1**	**S1**
	Peak Concentration H_2S, ppm	500[Ŧ]	500[Ŧ]	61	0.7	0.7
	Exposure Duration [†]	5:23	3:45	8:00	8:00	14:50
	TWA, ppm *	43	55	8.5	0.55	1.0
Exposure Guideline Exceeded	TLV-TWA	YES	YES	NO	NO	NO
	TLV-STEL	YES	YES	YES	NO	NO
	TLV-CEIL	YES	YES	YES	NO	NO
	IDLH	YES	YES	NO	NO	NO
	LC_{50}	YES	YES	NO	NO	NO

Ŧ Maximum detection range of sensor
† Time in hh:mm
* Based on indicated exposure duration

Conclusions

While this is a small representation of the population of Midwestern deep-pit swine facilities, it does provide preliminary results and information not previously documented. According to the results of the human exposure assessment, current normal operation conditions in deep-pit swine finish and gestation sow barns are not an exposure risk for swine workers.

Swine are also not at risk to overexposure to hydrogen sulfide during normal operation conditions in deep-pit swine finish and gestation sow barns. This is true even during cold weather seasons when barn ventilation is reduced to a minimum. The maximum concentration of all barns monitored during normal operation of was 2.1 ppm (barn F2) and the maximum TWA was 4.9 ppm (barn F2).

Swine remaining in barns during manure removal events with agitation are at risk to overexposure to hydrogen sulfide. The maximum concentration recorded during a manure removal event, 500 ppm (barns F1 and F2), was above the LC_{50} dosage. At this level swine could succumb to H_2S poisoning.

Hydrogen sulfide concentrations in deep-pit swine barns during manure removal events with agitation can exceed the IDLH and LC_{50} guidelines. These hazardous conditions warrant no entry for humans. Although conditions vary from barn to barn for manure removal events, there is increased risk of lethal H_2S environments during agitation events. In this study, in-barn H_2S concentrations were proportional to the degree of agitation aggressiveness. More aggressive agitation produced higher in-barn concentrations and thus a more dangerous environment. No agitation produced the lowest H_2S concentrations of all manure removal events in this study.

To protect swine during manure removal events no or minimal agitation is recommended when possible. Increased ventilation is recommended; should a burst occur ventilation can disperse possible high concentration H_2S from the barn. A commercially available hydrogen sulfide detection system can be used to alert workers to stop agitation and further increase ventilation to prevent dangerous H_2S conditions from persisting. If possible, ventilation controls should be installed outside or in a room isolated from the pit and in-barn air.

Manure applicators and swine workers should have a plan in the event of an H_2S related emergency. In the event of an emergency, agitation should be stopped and ventilation increased. Do not enter the barn if ventilation controls are located inside. If a worker has inadvertently entered the barn and collapsed, only those equipped with a self-contained breathing apparatus (SCBA) should enter to retrieve the victim. This would usually be local fire response services.

Further research to remove hydrogen sulfide from air in swine barns or manure agitation methods which minimize hydrogen sulfide releases is needed to reduce the risk of H_2S exposure to humans and swine. It is recommended a failure mode cause and effect analysis be performed. This would determine the critical safety components within a swine confinement and identify methods to improve their effectiveness.

Acknowledgements

This project is funded by a grant from the National Pork Board and the Iowa Pork Producers Association.

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CHAPTER 5. GENERAL CONCLUSIONS

This section will summarize the conclusions and implications of the research papers presented in this thesis. Discussion is included on the potential effects of the vertical manure pump design on hydrogen sulfide during manure slurry agitation. Future research ideas are also highlighted.

Wireless Hydrogen Sulfide Sensor Network

The wireless H_2S sensor network allowed research on a scale not feasible with a mobile lab due to costs, labor, and mobility requirements. One person easily transported, installed, and operated the network. The network takes less time to clean for biosecurity requirements than the infrastructure of a mobile lab. This reduction in downtime results in more barns monitored. At a component cost of $12,527, a 12 sensor network is equivalent to the cost of one H_2S analyzer. A mobile lab with a H_2S analyzer would be unable to capture the full range of H_2S levels experienced in the barns monitored during manure removal events with agitation. The sequential sampling method of a mobile lab is unable to get a snapshot of in-barn conditions. Furthermore, the mobile lab could have missed bursts of high concentration H_2S thus skewing the data towards lower concentrations.

The wireless network technology and self contained battery operated nodes reduced setup time and increased mobility of the entire wireless sensor network. Now that the wireless data transmission network has been developed it can be easily adapted to other projects and applications with other sensors or controls.

Contrary to a fluorescence analyzer capable of one function, the network can be disconnected from the sensors and adapted to other applications.

Spatial Distribution of Hydrogen Sulfide in Deep-Pit Swine Barns

Spatial distribution varied temporally and was dependent upon agitation and ventilation conditions within the four barns included in this study. The maximum detection limit of the sensor, 500 ppm, was reached during aggressive subsurface (F1) and aggressive surface agitation (F2). Summarized in table 5.1, the highest average and maximum concentrations recorded in barn F1 occurred where the manure was disturbed by the agitation jet colliding with a support pillar or encountering the slurry surface (locations 3 and 4). The mobile lab outside the barn prevented the wind from passing completely through the barn. This led to an area of insufficient ventilation (location 2) thus accumulating H_2S in the barn environment.

Table 5.1. Average and maximum hydrogen sulfide concentration at each of the 12 monitored locations in barn F1 during subsurface and surface agitation.

Height[†]	Location	Subsurface Agitation H_2S, ppm		Surface Agitation H_2S, ppm	
		$\overline{X}$	Maximum	$\overline{X}$	Maximum
0.1	1	30.13	110	8.36	76
0.1	2	79.89	376	8.07	356
0.1	3	23.59	171	79.60	408
0.1	4	74.00	500*	16.30	75
0.1	5	7.63	43	17.10	80
0.1	6	9.17	77	8.52	57
1.5	1	0.10	1**	0.10	1**
1.5	2	58.87	251	8.44	159
1.5	3	26.73	193	18.12	93
1.5	4	44.35	354	17.39	76
1.5	5	5.26	26	2.71	27
1.5	6	6.05	59	3.85	41

† Distance above slat floor in m

* Maximum detection limit of sensor

**Minimum detection limit of sensor

Hydrogen sulfide concentrations were lower during subsurface compared to surface agitation in barn F2 (table 5.2). The moderate subsurface agitation period in F2 produced the lowest in-barn H_2S concentrations of all barns with agitation in this study. This suggests the degree of agitation is a key factor in managing in-barn H_2S during manure pumpouts. Similar to F1, the highest average and maximum concentrations recorded in barn F2 occurred where the manure was disturbed by the agitation jet colliding with a pillar or encountering the slurry surface (locations 4, 5, and 6).

Table 5.2. Average and maximum hydrogen sulfide concentration at each of the 12 monitored locations in barn F2 during subsurface and surface agitation.

Height[†]	Location	Subsurface Agitation H_2S, ppm		Surface Agitation H_2S, ppm	
		$\bar{x}$	Maximum	$\bar{x}$	Maximum
0.1	1	0.00	0	20.06	83
0.1	2	4.38	15	57.11	218
0.1	3	10.74	16	81.61	216
0.1	4	7.96	40	99.23	417
0.1	5	7.85	21	145.73	455
0.1	6	5.18	15	140.10	500*
1.5	1	4.75	12	53.84	197
1.5	2	4.58	11	54.40	201
1.5	3	5.19	13	70.10	209
1.5	4	4.24	12	83.97	186
1.5	5	0.00	0	0.00	1**
1.5	6	Data unavailable due to sensor error			

† Distance above slat floor in m

* Maximum detection limit of sensor

** Minimum detection limit of sensor

The hydrogen sulfide concentrations in barn F3 during the manure pumpout (table 5.3) were much lower than the other two finish barns. However, the spatial distribution patterns were much the same. The highest average and maximum concentrations occurred in locations where the manure was disturbed by agitation or insufficient ventilation.

Table 5.3. Average and maximum hydrogen sulfide concentration at each of the 12 monitored locations in barn F3 during subsurface and surface agitation.

Height†	Location	Subsurface Agitation H_2S, ppm		Surface Agitation H_2S, ppm	
		$\overline{x}$	Maximum	$\overline{x}$	Maximum
0.1	1	6.32	57	10.05	51
0.1	2	3.35	18	6.01	47
0.1	3	5.08	39	3.07	33
0.1	4	7.18	44	3.74	17
0.1	5	1.34	29	2.91	52
0.1	6	0.08	7	1.78	18
1.5	1	1.97	21	4.88	40
1.5	2	3.33	20	8.47	61
1.5	3	3.10	19	1.46	11
1.5	4	3.47	17	1.34	13
1.5	5	0.05	7	0.63	16
1.5	6	0.09	7	1.54	16

† Distance above slat floor in m
* Maximum detection limit of sensor
** Mininum detection limit of sensor

Agitation resulted in a higher H_2S profile within a deep-pit barn during manure removal events compared to no agitation. However, not agitating slurry does not mix the settled solids into the slurry, thus not removing the solids from the pit. Over time the accumulation of solids within the pit will result in a loss of storage capacity. If left unresolved, the reduced storage capacity could lead to manure land application cycles that do not follow crop production cycles. In this event either a new disposal method, crop rotation, or additional storage is needed. Additionally, agitation is used to create a more uniform product for application as crop fertilizer. By distributing the solids within the slurry, the nutrient content increases which increases the nutrient value of the slurry. The increased value of the slurry permits land application at greater distances from the source.

There potentially were differences among H_2S concentration between locations within all finish barns before manure removal events. However, it is likely the detection limit (1 ppm) of the Pem-Tech PT295 HEC H_2S sensor masked these differences. The spatial distribution of H_2S after manure removal events in the finish barns was different due to ventilation differences. Barn F1 had a very uniform distribution of hydrogen sulfide following manure events because a moderate breeze provided adequate natural ventilation to the barn. Barn F2 had a relatively short after manure removal monitoring period in comparison to the other barns. It is likely the residual effects of H_2S released during manure agitation and the small sample period compounded this effect. Barn F3 had a north-northwest breeze encountering the corner of the barn and funneling wind between the barns. Personnel observed no wind exiting the leeward side in the western third of this barn. This effect resulted in higher average concentrations within this area.

The higher resolution H_2S analyzer enabled detection of lower hydrogen sulfide concentrations in the sow gestation barn (S1). If the wireless network had been the only monitoring system in this barn, it is likely no differences in spatial distribution would have been found. Overall, average concentrations increased with the distance to the end wall fans in the sow gestation barn (table 5.4). However, it could also be because this was the barn that used only mechanical ventilation. Since the wall curtains were closed during monitoring, air was entering the barn through the ceiling inlets. The effectiveness to move air from the end of the barn opposite end wall fans decreased when ceiling inlets provide the only means for introducing fresh air into the barn.

Table 5.4. Average and maximum hydrogen sulfide concentration at each of the 4 monitored locations in barn S1 during subsurface and surface agitation.

Height[†]	Location	Before Pumpout		During Pumpout		After Pumpout High Ventilation		After Pumpout Auto Ventilation	
		H_2S, ppm		H_2S, ppm		H_2S, ppm		H_2S, ppm	
		$\overline{X}$	Max	$\overline{X}$	Max	$\overline{X}$	Max	$\overline{X}$	Max
1.5	A	0.144	0.445	0.125	0.201	0.045	0.153	0.106	0.134
1.5	B	0.117	0.278	0.192	0.253	0.068	0.124	0.124	0.270
1.5	C	0.290	0.633	0.357	0.514	0.113	0.212	0.129	0.202
-0.1	D	0.578	1.187	0.528	0.709	0.110	0.277	0.153	0.235

† Distance above slat floor in m

This study concludes agitation is the source of hazardous high concentration H_2S released in the barn during manure pumpout events. By decreasing the duration of agitation or the speed of the engine powering the pump, risks associated with in-barn H_2S can also be decreased. This research confirmed locations nearest agitation activity and areas deficient in ventilation experienced the highest hydrogen sulfide concentrations during manure pumpouts.

Assessment of Hydrogen Sulfide Exposure in Deep-Pit Swine Barns

According to the results of the exposure assessment, current normal operation conditions in the deep-pit swine finish and gestation sow barns monitored, hydrogen sulfide is not an exposure risk for swine or swine workers. This holds true even during cold weather seasons when barn ventilation is reduced to a minimum. Three barns were monitored during normal operation conditions in this study. Two finish barns (F1 and F2) were monitored semi-continuously for five months. One sow gestation barn (S1) was monitored periodically for a total of four days. During normal operation the maximum time weighted average (TWA) exposure assessment for workers in barns F1, F2, and S1 were 1.2 ppm, 1.8 ppm, and 0.9 ppm, respectively. An eight hour work day was assumed for worker exposure duration. The maximum TWA for swine exposure on a 24 hour basis in barns F1, F2, and S1 were 3.4 ppm, 4.9 ppm, and 2.1 ppm, respectively. Hydrogen sulfide concentrations did not exceed any ACGIH, OSHA, or NIOSH exposure guidelines during normal operational periods.

During manure removal events with agitation in deep-pit swine barns, no human should enter a due to the potential for high hydrogen sulfide concentrations. The maximum detection limit of the sensor, 500 ppm, was reached during two aggressive agitation events. This concentration exceeds all ACGIH, OSHA, and NIOSH exposure guidelines and the LC_{50} dosage. This indicates there is increased risk of lethal H_2S environments during agitation events especially during aggressive agitation. In the sow gestation barn (S1), no agitation produced the lowest maximum H_2S concentration, 0.7 ppm, and maximum TWA, 1.0 ppm, of all manure removal events in this study. The non-agitation event in the sow gestation barn was not an exposure threat to workers or swine.

Manure applicators and swine workers should have a plan in the event of an H_2S related emergency. If a worker has inadvertently entered the barn and collapsed, only those trained and equipped with a self-contained breathing apparatus (SCBA) should enter to retrieve the victim. This would usually be local fire response services. Similar to controlled burns, custom slurry applicators should notify local fire services when and where manure slurry removal events are occurring. This would potentially decrease response time in the event of an emergency. Perhaps custom slurry applicators could form a cooperative to become trained with SCBA and purchase SCBA units for use in the event of H_2S related emergencies.

Effect of Vertical Manure Pump Design on Hydrogen Sulfide

A previous study by Arogo et al. (2000) concluded the bottom layers of deep-pit manure storage have higher solids content and lower pH and thus a higher potential for H_2S release. In this study aggressive agitation from a vertical manure pump led to lethal in-barn hydrogen sulfide. When a vertical manure pump operates in a swine deep-pit, it transfers power down a shaft to an impeller at the bottom of the pump. When used to agitate, the flow of the pump is directed back into the pit closer to the slurry surface or into the pit headspace (figure 5.1). In essence by agitating with this style pump, manure containing H_2S from the bottom layers of the pit is transported closer to the slurry surface or dispersed into the pit headspace thus increasing the potential for H_2S released into the air.

There are two advantages to agitating slurry by directing the flow back to the bottom of the deep-pit. 1.) The agitation jet at the bottom is closer to the settled solids enabling the solids to be more easily stirred up into the slurry. 2.) Manure returned to the bottom of the pit carries the H_2S within it to the bottom instead of dispersing into the air. This could potentially decrease the amount of hydrogen sulfide released into the air and barn.

Some custom manure applicators are moving away from agitation using vertical manure pumps. They are instead using flood agitation. Flood or “straw” agitation uses excess flow from a high volume pump and recirculates it through one or more pipes or “straws” around the building to the bottom of the pit. The goal of this agitation strategy is to agitate with volume instead of velocity.

Figure 5.1. A vertical manure pump draws manure and hydrogen sulfide from the bottom layers of the pit and recirculates it into the pit headspace to agitate or mix manure slurry.

Recommended Future Research

- Investigate manure agitation methods that can provide adequate mixing to dislodge settled solids and maintain safe in-barns H_2S levels
- Investigate the effects manure agitation which recirculates slurry to the bottom of the pit has on hydrogen sulfide releases
- Investigate effects of manure foam on H_2S production

- Building design and ventilation methods which prevent manure gases from entering the swine growing area

References

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