Title: Literature Review - Deep Pit Swine Facility Flash Fires and Explosions: Sources, Occurrences, Factors, and Management –

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Project Overview

During the fall of 2009, there were several reported incidences of Midwestern swine facility flash fires and explosions related to liquid manure agitation and pumping from deep pit concrete storage. Various institutions and organizations have been investigating the reported incidences and trying to identify possible factors and sources for the explosions and flash fires. Additionally, possible research studies, management modifications, and mitigation alternatives are being discussed. However, prior to committing resources to support specific projects, it was felt that a literature review relating to flash fire and explosion occurrences in deep pit swine facilities, sources, and factors should be performed. The following literature review was commissioned by the National Pork Board.

Selection of the primary content for the literature review was based on information known about swine production and deep pit swine facilities. Stored manure in deep pit swine facilities undergoes anaerobic decomposition during the time it is accumulated and stored in the facility. The gaseous by-products of manure anaerobic decomposition can include methane (CH_4), hydrogen sulfide (H_2S), and phosphine (PH_3), all of which are flammable gases that will combust with an ignition source, if present at high enough concentrations. Additionally, since 2001, inclusion rates of distiller's dried grains (DDGS) in swine diets have been increasing. There is conflicting data pertaining to the effect of DDGS inclusion rates on manure composition and gaseous emissions, but differences in feed composition between traditional corn/soybean diets and DDGS diets suggest there could be a difference in both composition and aerial emissions. Finally, in recent years, reported incidences of foaming in manure slurry stored in deep pit systems have increased, and several of the deep pit barn fires occurred on sites where foam was reported as present. Using the known information, pertinent publications were reviewed to provide background information and to better understand, explain, and substantiate potential reasons for the recent deep pit barn flash fires and explosions. Additionally, information pertaining to management to prevent barn fires was included.

Summary of Findings

Incidences of explosions and flash fires related to manure storage in deep pits were noted as early as 1969. Gases resulting from anaerobic decomposition of animal manure are the likely source of barn fires. Literature that specifically addressed which of the flammable gases is the problem (CH_4, H_2S, PH_3, or a combination of the three) was not available. However, methane was the only one of the three combustible gases that was reported as being measured at concentrations high enough to combust. Additionally, the lower explosive limit for both H_2S and PH_3 are far above the toxic level of these gases for both swine and humans. As such, animal death would occur before either H_2S or PH_3 reaches combustible levels within swine facilities. The reported literature verified there was significant potential for CH_4 generation from swine manure deep pit storage, and CH_4 concentrations in the flammable range were reported in deep pit swine systems.

Foaming in anaerobic systems has been reported to trap gases within the created bubbles. The reviewed literature suggested that foam which forms in swine manure deep pit systems can entrain or trap methane, and that when the foam is broken methane concentrations far above the lower explosive limit can be released. Methane is lighter than air; therefore once it is released from the foam, high levels could easily dissipate to explosive levels between 5 and 15% methane in air.

While foam may seem to be a possible cause associated with elevated gas levels, foam itself is likely an effect of another influence on the system. Because limited literature was available in relation to manures and foaming, information was sought related to foaming in municipal and industrial anaerobic systems. However, reasons for foaming in anaerobic sludge treatment systems and digesters are still somewhat theoretical and foam production is likely the result of multiple factors. For deep pit manure storage systems feeding DDGS rations, reduced water use during the cool summers, and choice of barn cleanser may contribute to foam production. Evidence indicated that DDGS inclusion in swine diets increased excreted manure volumes due to higher levels of indigestible fiber in the feed, and decreased water usage in the barn for animal cooling and hydration can result in more concentrated chemical and physical parameters in the manure.

Currently the best management practice that has been identified to reduce the risk of barn flash fires and explosions is to reduce the build-up of methane concentrations through adequate ventilation of deep-pit head-space. The majority of the reported flash fires and explosions were noted to have occurred during periods when pit-fans were not being operated, or when the fans were unable to provide significant air exchange due to limited pit head-space resulting from either high manure or foam levels in the pits. Many of the reported flash fires and explosions have been reported to have occurred when no animals were in the barns and ventilation was at minimal levels. During periods when no animals are in the barns, the use of pit exhaust fans to avoid build-up of methane in the pit head-space is suggested. When barn fans are more powerful than the pit exhaust fans, operation of only pit exhaust fans should be considered to avoid drawing additional gases in the animal area when barns are empty. It is also important that adequate head-space in the deep-pit be maintained to allow effective operation of the pit exhaust fans. While the foam noted to have been formed in many barns prior to fires is not the source of the methane, the foam does trap methane that would otherwise be removed from the pit head-space by ventilation. As such, it would be helpful to develop methods to decrease or stop the formation of foam in deep-pit swine manure storage systems.

This literature review did not identify sufficient information to fully explain the sources of foam formation and control in swine manure storage systems. Some compounds used to clean barns could inadvertently enhance foaming. Ionic detergents are known for their foaming ability, while non-ionic detergents can have properties that act as de-foamers. Antifoaming agents have potential, but foam collapse and antifoaming characteristics are not fully understood. Literature suggests the best way to determine the effectiveness of an antifoaming agent is to conduct performance tests for each suggested antifoaming agent. Literature has shown that foam suppression is a result of the balance between various surface active agents including the amended foam. Specifically, while some agents were capable of destroying a foam in one processes, the same agent acted as a foam stabilizer in another.

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Flash Fire and Explosion Occurrences

<u>Historical Record of Reported Flash Fires and Explosions</u>

Explosions in manure storage pits have been reported in literature since 1969 (Choiniere, 2004; Donham, 1982; Muehling, 1969). Muehling (1969), at the University of Illinois, noted the occurrence of "several" explosions in manure storage pits above slatted floors. Donham (1982), at the University of Iowa, noted the occurrence of "a few isolated" explosions from methane in deep pits over slatted floors with four to six months of storage.

During the winter of 2003, two successive explosions occurred in a multi-room, mechanically ventilated, finishing pig deep pit facility near Victoriaville, Quebec, Canada. Choiniere (2004) prepared a paper summarizing the incident and the succeeding investigation. Successive explosions occurred on February 18, and March 5, 2003; methane (CH_4), carbon dioxide (CO_2), hydrogen sulfide (H_2S), and ammonia (NH_3) levels were evaluated at the site on March 24, 2003. Foaming was present at the facility and the explosions occurred after facility wash water flowed into the deep pit. Animal diet was not listed. Gas concentration measurements were made in the barn after ventilation was turned off. One hour after shutting off mechanical ventilation gas concentrations were measured as 0.2% CH_4. Methane levels of 0.5 – 0.7 % were noted within 4 to 8 hrs after shutting off mechanical ventilation. Throughout the data collection H_2S levels were between 1-2 ppm. Choiniere (2004) concluded that the explosions were likely the result of wash water flowing into the storage pit, popping the foam's bubbles, and subsequent release of CH_4. During pit agitation and manure removal, CH_4 concentrations were measured between 2 to 4% (whether or not the foam was still present was not reported).

Multiple deep-pit, manure storage related barn fires occurred during the fall of 2009. Information was available for five of the fires. Three of the incidents were reported in local media (Springer, 2009; Theisen, 2009), and two were visited by Iowa State University Animal Waste Management Laboratory (AWML) staff (Muhlbauer, 2009). All five incidents occurred at swine finishing sites with sub-floor slurry storage. In four of the events the barns were empty, and had recently been washed with detergent, disinfectant, or hot or cold water, and thick foaming was present in the slurry pits. Four sites experienced flash fires within 20 minutes of initiating slurry agitation. At three of the four sites, the heaters were on in the facilities when the fires occurred, and are believed to have been the ignition source. The fifth event happened while welding maintenance was being performed. In this instance, sparks fell into the pit, ignited the foam, and resulted in a fire that consumed the majority of the facility. Foam was collected and sampled for CH_4 and H_2S by the ISU-AWML team at two sites visited after the fires had occurred, and at a third site with foam where no fire had occurred. Methane concentrations within the foam were found to range from 50% to 65%, and hydrogen sulfide was found to be 250 ppm or less.

Flash Fire and Explosion Sources

<u>Background Information for Methane, Hydrogen Sulfide, and Phosphine</u>

Storage of liquid manure in deep pits results in anaerobic conditions that provide a favorable environment for anaerobic and facultative microbes (Donham, 1982). These microbes carry out anaerobic decomposition of manure and result in creation of multiple gases including CH_4, NH_3, H_2S, phosphine (PH_3), and CO_2. Conversion of a complex organic material to gaseous by-products requires three distinct steps; 1) hydrolysis, 2) fermentation and anaerobic oxidation, and 3) methanogenesis.

Hydrolysis is the name given to the enzymatic process of degrading complex polymers into smaller sub-units capable of being transported into a microorganism cell. When carbohydrates, proteins, and lipids are hydrolyzed, simple sugars, amino acids, and long chain fatty acids result. For manures, hydrolysis is an important first step in anaerobic digestion. The fibrous and complex organic materials in manures are converted to material that can be consumed by the microorganisms. Microorganisms then convert simple sugars, amino acids, and long chain fatty acids into propionate, butyrate, acetate, CO_2, and hydrogen (H_2) through a process referred to as fermentation and anaerobic oxidation. Anaerobic oxidation also refers to the subsequent conversion of the propionate and butyrate to acetate or CO_2 and H_2. Existence of acetate or CO_2 and H_2 are required for the production of CH_4 and CO_2 in the anaerobic digestion process. Methanogenesis is the term used to describe the final step in the anaerobic digestion process. Methanogenic microorganisms form CH_4 and CO_2 from acetate or from CO_2 and H_2. Depending on the characteristics of the digester influent, other gases can result. Phosphine and H_2S are gaseous by-products formed during anaerobic decomposition of manure. Table 1 presents the lower explosive limits and upper explosive limits in air as both a percentage and ppm value for each of these gases.

Table1. Explosive limits for methane, phosphine, and hydrogen sulfide.

	Lower Explosive Limit (%), (ppm) in air	Upper Explosive Limit (%), (ppm) in air
Methane	5%, 50,000 ppm	15%, 150,000 ppm
Hydrogen Sulfide	4.3%, 43,000 ppm	46%, 460,000 ppm
Phosphine	1.8%, 18,000 ppm	98%, 980,000 ppm

Methane

In a paper addressing gases and odors from stored swine wastes, Muehling (1969) provided an overview of characteristics and information related to CH_4 and H_2S. Methane is a colorless and odorless gas with a density of 0.72 g/L at 0°C and 1 atm, which is lighter than air. It is produced from decomposition of organic matter under anaerobic conditions. Methane is not very soluble in water, but it is highly flammable. In manure storage pits, CH_4 can rise from its place of generation and accumulate in stagnant corners (Muehling, 1969). At concentrations in the range of 5 to 15% (50,000 to 150,000 ppm), any small spark can cause a dangerous explosion. In a study by Zahn et al. (2000), methane concentrations measured in deep pit facility air samples were less than 10 ppm (during this study, animals in the deep pit barns were not receiving distillers dried grains with solubles (DDGS)). See the following section "Typical Deep Pit Gas Levels" for further information about the study performed by Zahn et al. (2000).

Hydrogen Sulfide

Hydrogen sulfide is a colorless gas with an odor of rotten eggs and a density of 1.54 g/L at 0°C and 1 atm, which is heavier than air. It is produced from the decomposition of organic matter when sulfur is present under anaerobic conditions. Muehling (1969) reported that H_2S explodes violently at a mixture of 1.24 times its volume in oxygen, and that it is one of the more toxic gases associated with liquid manure storage. The MSDS sheet for H_2S reports it is flammable between 4.3 and 46% (43,000 and 460,000 ppm) (Praxair, 2009). In 1982, Donham reported that H_2S levels in deep pit facilities were around 10ppm during standard operating conditions, but that under certain conditions such as manure removal and agitation, manure pits could create extremely high levels (>500 ppm) that could result in acute toxic effects to humans in the vicinity.

Phosphine

Zhu et al. (2009) described two forms of PH_3, free gaseous PH_3 and matrix bound PH_3. Matrix bound PH_3 (sometimes referred to as biogenic phosphine) was defined as being bound to environmental materials such as manure, human feces, and lake sediments that could be released during anaerobic conditions (Zhu et al., 2009; Gassmann and Glindemann, 1993). Gassman and Glindemann (1993) utilized alkaline, anaerobic assays to liberate and measure gaseous phosphine. Zhu et al. (2009) utilized an acidic digestion and an alkaline digestion in an anoxic nitrogen atmosphere, as well as an anaerobic assay to liberate gaseous PH_3. In both studies, all assays were capable of producing PH_3. Gaseous PH_3 is highly toxic, and it produces an acute, lethal effect on humans by inhibiting aerobic respiration (Zhu et al., 2009; AirLiquide, 2009). The lethal concentration (LC_{50}) is 11 ppm (Praxair, 2009). Matrix bound PH_3 has been reported to be present in ruminant and swine feces; consequently it ends up in systems such as manure storage tanks and anaerobic digestion processes (Eismann et al., 1997). Cattle and swine manure samples collected and analyzed in Germany reportedly had 13.9 and 964.1 ng PH_3/kg of sample, respectively (Gassmann and Glindemann, 1993). Biogenic PH_3 has been reported to occur with the presence of methane and has lead researchers to believe there is a correlation between methanogenesis and the reduction of phosphate to PH_3 in nature. Phosphine has been found (Devai et al., 1988) and formed (Haifeng et al., 2000) in anaerobic conditions.

Phosphine gas has a garlic or onion like odor, it can begin to have negative effects on humans at 0.3 ppm, and it has been classified as a pyrophoric gas (AirLiquide, 2009). Pyrophoric materials can spontaneously ignite in air. Heavier than air, its density is 1.45 g/L at 15°C and 1 atm. Phosphine gas and air mixtures are explosive (AirLiquide, 2009), with an auto-ignition temperature listed as 38°C (IPCS, 2009). The MSDS sheet for PH_3 indicates it is flammable between 1.8% and 98% in air (Praxair, 2007).

<u>Typical Deep Pit Gas Levels</u>

In this review, an attempt was made to report H_2S and CH_4 concentrations in the deep pit head space, or in deep pit barns at a sampling location just above the slats. When possible an indication was provided as to whether or not the facility included in the study was feeding DDGS. In many cases this information was not provided; however the date of data collection may provide some insight. After conferring with his peers, Dr. Alan Sutton (2009) indicated that it probably wasn't until 2001 that pork producers began to feed DDGS more frequently. Unfortunately, no gaseous emission monitoring studies were found in literature that clearly stated the data was collected from deep pit manure storages where DDGS was being fed. Two studies are known to be in progress to collect data from deep pit facilities containing animals receiving DDGS, but neither project has results available at this time. The two known studies are being conducted by Dr. Robert Burns at Iowa State University and Dr. Scott Radcliffe at Purdue University.

For this review, concentration data and not emission rate information were necessary to determine explosive potential of gases within deep pit facilities. Additionally, this review specifically focused on obtaining concentration data that was collected near the level of the slatted floor, in the head space of the storage pit, or from the pit exhaust fans. Three studies were identified that provided gaseous concentrations within deep pit manure storage facilities (Zahn et al., 2000; Patni and Clarke, 2003; and Hoff et al., 2006).

Zahn et al. (2000) reported average emission and concentration data (for NH_3, CH_4, H_2S, and volatile organic compounds (VOC)) and average physical and chemical properties (volatile solids (VS), total solids (TS), pH, carbon, hydrogen, nitrogen (N), phosphorus (P), potassium

(K), and micronutrients) for four types of swine facility waste management systems. The four types of facilities were sampled in August and September of 1997 in Iowa, Oklahoma, and North Carolina and included 1) deep pits and a pull plug system, 2) outdoor earthen or concrete lined basins and a steel tank, 3) lagoons, and 4) phototrophic lagoons (lagoons containing purple sulfur bacteria shown to emit reduced odor levels). Data for pull plug systems and deep pit systems was presented as an average in this paper. This was also the case for outdoor earthen and lined basins. Deep pit and pull plug systems are inherently different; however, five of the six systems in the Type 1 category were deep pits, and the standard deviations presented with the averages are low.

For the Zahn et al. (2000) study, the air samples were collected near the liquid surface. For deep pits, the sample line was inserted between the slats at a level just above the manure slurry; the deep pits were estimated to be ¾ full (Hatfield, 2009). Air samples for H_2S and CH_4 were collected in Tedlar bags using a 1062 Supelco grab sampler, and gas was analyzed in the laboratory with a gas chromatograph. Air samples for NH_3 were collected using two glass impingers in series; air was drawn through a fritted glass diffusion tube into 60 mL of boric acid. The ammonium concentration was determined using the salicylate-nitroprusside technique (U.S.EPA method 351.2). Air samples for VOCs were collected in thermal desorption tubes using a low volume sampling method they developed and analyzed by gas chromatography (Zahn et al., 2000). Expected result uncertainty, based on instrumentation and procedure specifications, was not provided.

During the Zhan et al. (2000) study, animals in the deep pit barns did not have DDGS included in their diets (Hatfield, 2009). The average concentration of CH_4 and H_2S in the pits just above the manure slurry was 7.5 and 0.037 ppm, respectively. Data from this study is presented in Table 2. The highest CH_4 concentrations were obtained above the lagoons, with the highest concentration occurring above the phototrophic lagoons. Because lagoons contain more dilution water, nutrient and solids concentrations were greater in the pits below slatted floors and the storage tanks and basins.

Table 2. Average concentration of physical and chemical properties and trace gases present in manure and air samples collected from four types of swine manure management systems, table adapted from Zahn et al. (2000).

Parameter	**Site Classification***			
	Type 1	**Type 2**	**Type 3**	**Type 4**
Waste management system, No. of sites	DP, 5 PP, 1	EB, 3 CLB, 3 ST, 1	L, 6	PL, 10
VS loading rate (kg / day·m^3)	79 ± 3.0	35 ± 2.6	0.3 ± 0.05	0.07 ± 0.02
CH_4 flux rate (g / system·hr)	636 ± 47	1830 ± 148	13,900 ± 760	11,990 ± 540
pH	7.1 ± 0.04	7.3 ± 0.06	7.3 ± 0.06	7.1 ± 0.03
TS (%)	2.19 ± 0.09	1.34 ± 0.06	0.38 ± 0.04	0.28 ± 0.01
N (mg/L)	657 ± 44	389 ± 27	68 ± 7.6	42 ± 2.8
P (mg/L)	504 ± 26	153 ± 12.1	65 ± 4.5	0.2 ± 0
Ammonia (ppm), at 20°C, 1 atm	12.5	10.3	12.2	14.1
Methane (ppm), at 20°C, 1 atm	7.5	13	28	37
Hydrogen Sulfide (ppm), at 20°C, 1 atm	0.037	0.033	0.019	0.020

* Where DP is deep pit, PP is pull plug, EB is earthen basin, CLB is concrete lined basin, ST is steel tank, L is lagoon, and PL is phototrophic lagoon

Patni and Clarke (2003) reported H_2S, NH_3, and CO_2 concentrations in 10 commercial swine barns with fully slatted floors and sub-floor slurry storage prior to, during, and immediately after slurry mixing. All of the barns had mechanical ventilation, and eight of the nine barns had pit exhaust fans in addition to the barn exhaust fans. Where possible, the pit fans were in operation at the time of the concentration measurements; measurements were made at floor level and 0.9 m above the floor and from pit exhaust air. For H_2S, one minute average concentrations were monitored at six locations using Draeger electrochemical sensors. Time weighted average concentrations of NH_3, H_2S, and CO_2 were obtained with Draeger long-term, diffusion type gas detector tubes, and short term detector tubes with bellow pumps were used for spot checks. Expected result uncertainty, based on instrumentation and procedure specifications, was not provided. Manure samples were collected following several hours mixing, and they were analyzed for temperature, pH, conductivity, TS, NH_3, and volatile fatty acids. An attempt was made to contact the authors, but it could not be determined whether or not DDGS was being fed during the time these samples were collected.

Results from this study are summarized in Table 3. The authors reported that H_2S concentrations were below hazardous levels (15 ppm for short term exposure, 10 ppm for long term exposure) except for during agitation and mixing, at which time concentrations rose rapidly to very high values. Ceasing agitation and mixing rapidly decreased H_2S concentrations. The H_2S concentration varied with time and location in the barn. The authors concluded that well functioning exhaust fans and avoidance of splashing and free falling manure in the pit during agitation reduced H_2S concentrations above the slatted floors. Additionally, they indicated slurry mixing and barn air movement were more important to H_2S release than manure composition.

Hoff et al. (2006) reported concentration and emission rates of $NH_{3,}$ H_2S, and odor from pit, tunnel, and sidewall fans before, during, and after slurry removal from a deep-pit swine finisher. Data was collected during October 2002 and October 2003. Ventilation during slurry agitation and removal followed the producer's strict protocol set to obtain 30 air exchanges per hour. Concentrations were measured at 12 locations using a TEI Model 17C chemiluminesence monitor for NH_3, a TEI Model 45C pulsed florescence unit for H_2S, and an MSA IR Model 3600 for CO_2. Each sampling location was monitored for 10 minutes every 120 minutes throughout the pump-out events. Expected result uncertainty, based on instrumentation and procedure specifications, was not provided. The author was contacted, but it could not be determined whether or not DDGS was being fed during the time these samples were collected.

Hydrogen sulfide concentrations measured in the pit fan exhaust are shown in Table 4. Hoff et al. (2006) reported that the on average, the H_2S concentration in the pit fan exhaust reached a level 18 times higher during agitation as compared to the before removal level.

<u>Occurrence of Elevated Flammable Gas Levels</u>

During the fall of 2009, multiple deep pit barn fires occurred. Following the fires, two of the sites were visited by Muhlbauer (2009) representing Iowa State University. Information about these two fires has been included within this literature review to provide background information related to the fires and circumstantial evidence relating to how and why the deep pit fires and explosions have been occurring.

At a site in southeast Iowa, an explosion occurred during agitation in preparation for slurry removal from the pit. The producer had been feeding DDGS and foam was present in the deep pit. After animals were removed from the facility, it was washed with a high foaming, highly soluble disinfectant and detergent. Prior to slurry removal, the manure had been sampled and contained the following 6% TS, 7,600 mg/L nitrogen, 3,200 mg/L phosphorus, 4,700 mg/L potassium, and 800 mg/L sulfur. Pit fans and heaters were running during agitation; however,

Table 3. Site information and corresponding sample concentrations, table adapted from Patni and Clarke (2003).

Site-Visit No.	Pit Depth (m)	Manure Depth (m)	Head Space (m)	Mixing Type*	Animal Type**	Max. H_2S (ppm)		Avg. Pit H_2S (ppm) at Various Locations		Sampled After Mixing					
						Pit Exhaust	Barn Air	Pit Exhaust	Barn Air	Sample Depth (m)	Temp. (°C)	pH	TS (%)	N (mg/L)	Volatile Acids (mmol/L)
1-1	3	1.8	1.2	RP	F	--	0	---	0						
1-2	3	1.5	1.5	RP	F	15	0	0-2	0	0.6 1.2	16 16	7.2 7.2	1.1 1.1	2900 2900	10 18
1-3	3	1.5	1.5	RP	G	19	0	0-3	0	0.6 1.2	16 16	7.2 7.1	2.0 2.0	3400 3500	13 14
2	1.8	1.2	0.6	RP	G	112	3	0-19	0						
3-1	3	1.5	1.5	SP	G-F	116	100+	16-74	4-10						
3-2	3	1.5	1.5	SP	G-F	236	50	2-11	0	0.6 1.2	--- ---	8.0	2.3	3800	10
4-1	3	3	0.0	AB	G-F	222	10	0-13	0						
4-2	3	1.2	1.8	AB	G-F	44	20	0-1	0	0.6	---	8.1	1.4	3300	5
5-1	2.4	1.4	1.0	SP	G-F	272+	45	2-39	2-4	0.6	24	7.6	3.9	6200	104
5-2	2.4	1.1	1.3	SP	G-F	365	64	72-164	5-9	0.6	---	7.7	6.7	5400	20
6-1	2.4	1.8	0.6	SP	G	262	213	3-28	8-15	0.6	24	7.6	1.5	3000	2
6-2	2.4	1.0	1.4	SP	G	140	129	4-6	2-5	0.6	---	7.7	1.3	3000	22
7	2.4	1.8	0.6	SP	G-F	179	165	10-11	4-10	0.6	---	7.7	2.3	4100	245
8-1[#]	2.4	2.1	0.3	AB	G-F	---	1300	---	9-98	0.6	---	7.5	1.6	4100	101
8-2[#]	2.4	2.1	0.3	AB	G-F	---	1000	---	2-30[+]						
9	2.4	2.1	0.3	RP	W	61	220	1	4-33[+]	0.6	---	7.7	2.6	3000	1
10	2.4	2.4	0.0	RP	G-F	0	0	0	0	0.6	---	7.8	1.4	3100	2

*RP is recirculation PTO pump, SP is submerged pump, AB is air blowing
**W is weaner, G is grower, G-F is Grower-Finishing, F is Finishing
[#] Site 8 does not have a pit exhaust fan

the foam in the pit was within approximately 45 cm (18 inches) of the slats, likely reducing the effectiveness of the pit fans. During agitation, the operator noticed the foam disappear (in less than a minute). Then he noticed the curtain walls bow outwards approximately 45 cm (18 inches). This was followed by a flash explosion with no residual fire. At the time the site was visited by Muhlbauer (2009), foam was still present. Methane content within the foam was analyzed and ranged from 29 – 73%. An analysis of H_2S concentrations in the foam was not conducted.

Table 4. Hydrogen Sulfide concentration in pit fan exhaust before, during, and after slurry removal, table adapted from Hoff et al. (2006).

Year	Barn	Avg. Before (ppb)	Max During (ppb)	Avg. After (ppb)	Date
2002	1	272	9,990*	79	Oct. 16, 2002
2002	2	1,084	5,455	31	Oct. 18, 2002
2003	1	397	850	467	Oct. 21, 2003
2003	1	467	22,245	69	Oct. 22, 2003
2003	2	2,067	35,852	93	Oct. 20, 2003

*Exceeded maximum range of the analyzer which was 10,000 ppb; analyzer was subsequently changed to a range of 50,000 ppb

At a site in northeast Iowa, an explosion occurred during a welding repair within the barn. The producer had been feeding DDGS and foam was present in the deep pit. After removing animals from the facility, the barn was washed with hot water. At the time of the fire, no pit fans were running, but the side curtains were halfway down. The welder working in the facility noticed a 30 cm (12 inch) ring of fire in the pit below him. He left to obtain something to put out the fire, but upon return, the fire was reaching through the slats and ignited the barn. At the time the site was visited by Muhlbauer (2009) foam was still present. Methane content within the foam was analyzed and ranged from 14 - 50%. An analysis of H_2S concentrations in the foam was not conducted.

The CH_4 and H_2S content in foam at a third deep pit finish barn in central Iowa was measured by the ISU-AWML team in the fall of 2009. No fire had occurred at this facility, but foam has formed on top of the stored manure. The foam contained from 60 – 66% CH_4 and from 180 to 220 ppm H_2S (Muhlbauer, 2009).

Additionally, information available in literature has indicated gas levels in pit head-spaces where manure is stored below slatted floors can increase with length of storage. Haeussermann et al., (2006) performed a research study at a pig facility in Southern Germany. In the study, manure was stored below the animals that were housed in two pens on slatted floors. The study was undertaken in October 1999 – February 2001 and February 2003 – July 2004. The authors examined the influence of season, ventilation, and slurry removal on CH_4 emissions. Methane measurements were made in the inlet and exhaust air, but not at the slatted floor or pit level. Additionally, only emission rates were reported, concentration data of the exhaust air was not included. Results indicated that CH_4 emission rates were correlated to time of manure storage; specifically, the CH_4 emission rate increased as manure storage time increased.

Possible Factors Effecting Suggested Sources

Foaming and Why Foaming Occurs

Foaming has been reported to be an issue in both aerobic and anaerobic waste treatment systems (Ganidi et al., 2009; Pagilla et al., 1997; Cumby, 1987). It has also been noted that foaming can be a problem in animal slurries undergoing aeration (Cumby, 1987). Foaming has been noted in some anaerobic treatment systems and is a concern due to impacts on process efficiency and operational costs (Ganidi et al. 2009; Barber, 2005; Pagilla et al., 1997). Foaming has been shown to invert the solids profile of anaerobic digesters, with higher solids concentrations at the top of the system than the bottom of the system (Pagilla, et al., 1997). Vardar-Sukan (1988) noted that when foaming occurs in bioprocesses, productivity losses include loss of working volume and "enhanced gas hold-up" (interpreted to mean gas storage in the foam). Ganidi et al. (2009) indicated foaming caused inefficient gas recovery, which while not clearly stated is likely a reference to gas collection in the foam preventing its recovery in the biogas system. Unfortunately, no published literature was found regarding foaming in static or mixed manure storage systems.

Due to deep pit manure storage conditions, these systems would generally be considered anaerobic. In anaerobic systems, multiple sources have been suggested as mechanisms for foaming (Ganidi et al., 2009). Suggested sources include natural and synthetic detergents, oils and greases, proteins, lipids, and polymers, and residual filamentous bacteria from aerobic treatment (Barber, 2005; Hernandez and Jenkins, 1994; Ghosh, 1991). The suggested foaming sources have been classified as either surface active agents or filamentous microorganisms.

Surface Active Agents

The prerequisites for foaming are availability of surface active agents, a gaseous phase, and hydrophobic material (Barber, 2005). Surface active agents affect liquid surface tension by either increasing or decreasing the liquid surface tension. Both types of surface active agents can exist in systems with biological processes. Surface active agents that lower or reduce a fluid's surface tension tend to increase the potential for foaming (Barber, 2005). Surface active agents can be either surfactants (lipids, volatile fatty acids, detergents, or proteins (Ganidi et al., 2009) or bio-surfactants (substances produced during metabolic activity such as fatty acids, proteins and lipid complexes, extracellular polymers, and soluble microbial products (Ganidi et al., 2009; Barber, 2005)). To decrease surface tension, the hydrophobic end of the agent is forced out of the liquid towards the air phase, and the hydrophilic end of the agent moves toward the liquid phase (Ganidi et al., 2009). A gaseous phase within the biologic system can exacerbate foaming (Barber, 2005); by attaching to themselves to gas bubbles and allowing hydrophobic materials rise to the liquid surface.

Literature has suggested that the surfactants existing as proteins, lipids, volatile fatty acids, and detergents have all been attributed to foaming (Barber, 2005; Ganidi et al., 2009). Proteins have been recognized as foam forming agents, and concentrations above which foaming may occur for specific proteins have been identified for some compounds (Ganidi et al., 2009). Volatile fatty acids are generally low in molecular weight and soluble in water. As a product of the anaerobic decomposition process, their formation precedes methane production. When anaerobic process become instable or have been organically overloaded, volatile fatty acid concentration in these systems typically increases. Accumulation of acetic acid (one of the more prevalent volatile fatty acids in anaerobic systems) has been identified in the literature as a cause for foam formation (Ganidi et al., 2009). Lipids can exist in anaerobic systems as fats and oils. Ganidi et al. (2009) theorize that lipids could contribute to foaming due to gas entrapment on the compounds and the surface active properties of lipids; however, they were unable to substantiate that theory because additional data demonstrating the contribution of lipid to foaming potential was not found in literature. Ganidi et al. (2009) also indicated that anionic detergents have surface active properties that could contribute to foaming, specifically a group of domestic and industrial detergents referred to as linear alkylbenzene sulphonates.

Information about the effect of bio-surfactants on foaming is limited. Limited bio-surfactants have been tested to establish concentrations at which they decrease surface tension (Barber, 2005). Bio-surfactants exist in non-foaming anaerobic systems, but elevated levels can occur with anaerobic system instability and organic overloading (Ganidi et al., 2009). The likely hood of bio-surfactants to enhance foaming may be dependent on the type and concentration of bio-surfactants present.

Ganidi et al. (2009) concluded that a large number of surface active agents are present in anaerobic systems, but the effect of each agent on foaming is dependent on its properties and concentration. Their review of foaming literature led them to believe proteins may have the greatest effect because they are less biodegradable than lipids and fiber, presence of anionic detergents may be an issue due to their low solubility under anaerobic conditions, and high levels of acetic acid may be an issue which can be the result of fluctuations in anaerobic systems. Barber (2005) noted that volatile fatty acids are likely the most abundant surface active agents in anaerobic systems, but they may not be the most active, and that a number of other bio-surfactants can be excreted if overloading or toxicity issues occur within the system.

As the concentration of surface active agents increase, the compound's molecules begin to form clusters (micelles). Therefore, the critical micelle concentration may be useful in establishing at what concentration surface active agents must exist to cause foaming problems. The critical micelle concentration is the concentration of the agent necessary to reduce the liquid's surface tension. The critical micelle concentration of a compound determines the concentration beyond which surface activity increases, and where foaming would appear if bubbles were introduced into the solution (Ganidi et al., 2009). In the case of deep pits, the bubbles could be the result of CH_4, H_2S, and CO_2 generated within the stored slurry and rising to the top of the liquid level.

Surface tension tests for each suspected surface active agent would be necessary to determine the critical concentrations necessary to induce or stabilize foaming during anaerobic digestion (Ganidi et al., 2009). It has been noted that organic overloading of anaerobic systems could be a primary cause for surface active agent foaming (Ganidi et al., 2009; Pagilla et al., 1997; van Niekerk et al., 1987). Organic overloading could lead to excess surfactant and bio-surfactant concentrations, leading to accumulation of hydrophobic or surface active by-products that would promote foaming (Ganidi et al., 2009).

Filamentous Organisms

Filamentous organisms have also been suggested to be a cause for foaming in municipal anaerobic sludge digesters associated with aerobic activated sludge systems. Accumulation of filamentous organisms on the liquid surface in municipal anaerobic systems along with bio-surfactant production potentially could result in reduced surface tension of the liquid and enhanced foaming potential (Barber, 2005). Specifically, the filamentous bacterial species *Nocardia* and *M. parvicella* have been associated with foaming in municipal sludge digesters. However, these organisms have been shown to exist in anaerobic systems as residuals from the system's upstream aerobic activated sludge process (Ganidi et al., 2009). Hernandez and Jenkins (1994) reported that *Nocardia* is a known obligate aerobe, and found that the bacteria could survive in anaerobic systems for more than 14 days. Because aerobic activated sludge material would not generally be introduced to deep pit manure storage, it was not likely that *Norcardia* would exist in a deep pit manure storage system.

<u>Diet Modifications</u>

Construction of large scale ethanol plants in the Midwest has increased the availability of DDGS. Until 2001, 96% of the DDGS being fed to animals in the US was fed to cattle with only

4% utilized in swine and poultry feed, but by 2003 15% of the DDGS produced in the US was being utilized in swine rations (Shurson et al., 2004). Distillers dried grains with solubles provides lysine, phosphorus, and energy, and it can be used to replace soybean meal, dicalcium phosphate, and corn in swine diets (Thaler, 2002). During the ethanol production process and subsequent process to produce DDGS, nutrient concentrations of the original corn grain can increase by as much as three-fold (Shurson et al., 2004). Although there is still considerable variation in nutrient content and digestibility of DDGS among sources, the newer ethanol plants produce a product with higher levels of essential nutrients than was previously thought by animal nutritionist (Shurson et al., 2004). This led swine nutritionist to reconsider DDGS as a feed source for pigs, and increased its use as a feedstuff today. Thaler (2002) reported nutrient and physical property ranges for nine DDGS samples. They were as follows; dry matter 87-93%, crude protein 23-29%, crude fat 3-12%, and lysine 0.59 to 0.89%. Maximum inclusion rates reported in 2009 were slightly higher than those provided in 2002; the 2009 rates reported by Stein and Shurson (2009) were 30% for nursery pigs (from 2-3 weeks post weaning), 30% for grow-finish pigs, 30% for lactating sows, and 50% for gestating sows. Thaler (2002) reported a maximum 50% inclusion for boars.

A few studies were available related to DDGS inclusion in swine diets, manure excretion, and gaseous and odor emissions (Powers et al., 2008; Powers et al., 2006; Xu et al., 2005; Gralapp et al., 2002; Speihs et al., 2000). These studies were all performed in research trials containing 16-72 animals. Hydrogen sulfide was monitored in two studies, but the reported results from each study were contradictory (Powers et al, 2008; Spiehs et al., 2000). One study evaluated the effect of DDGS inclusion on CH_4 emissions and found no effect (Powers et al, 2008), but no studies were found in relation to phosphine. One study measured manure production volumes from animals receiving both DDGS and non-DDGS rations, and these results indicated that manure output volume was significantly increased with DDGS inclusion in the diet (Xu et al., 2005).

Spiehs et al. (2000) performed a 10-week trial on 16 barrows weighing ~57 kg. Half of the animals received 20% DDGS in their diet, and the other half received 0% DDGS. Manure and air samples were taken throughout the study. Dietary treatment was found to have no effect on H_2S, NH_3, or odor emissions in this study; CH_4 was not analyzed. Diets containing DDGS had higher nitrogen levels, so while nitrogen retention was the same for both study groups, feeding DDGS increased nitrogen excretion. The DDGS inclusion rate utilized in this study was less than the current (2009) reported maximum inclusion rate; the current maximum inclusion rate is 30% for finishing pigs, this study, performed in 2000, utilized a DDGS inclusion rate of 20%.

Gralapp et al. (2002) performed six, four-week trials utilizing a total of 72 finishing pigs. Three diets containing 0, 5, and 10% DDGS were fed during the study. Manure from the study was collected in a pit below each animal group; samples for manure and odor analyses were collected on day 4 and day 7 of each week; and manure pits were cleaned once a week. Between diets, Gralapp et al. (2002) observed no significant differences between concentrations of total solids (TS), volatile solids (VS), chemical oxygen demand (COD), total Kjeldahl nitrogen, or phosphorus content ($P>0.10$). Additionally, there were no significant treatment effects on odor dilution threshold. The DDGS inclusion rates utilized in this study were considerably less than the current (2009) reported maximum inclusion rate; the current maximum inclusion rate is 30% for finishing pigs, this study, performed in 2002, utilized DDGS inclusion rates of 5 and 10%.

Xu et al. (2005) performed a study utilizing 40 nursery pigs to evaluate phosphorus excretion from animals receiving DDGS diets. The diets contained 0, 10, and 20% DDGS. Results indicated that diets containing 10 and 20% DDGS had a 15 and 30% increase in daily manure output, respectively, compared to pigs fed the corn-soybean meal diet. Xu et al. (2005) reported the increase was due to a 2.2 and 5.1 % reduction in dry matter digestibility in the rations containing 10 and 20% DDGS, respectively. Reportedly, reduced dry matter digestibility was the result of excess crude protein and higher fiber levels in the DDGS diets. The DDGS inclusion rates utilized in this study were less than the current (2009) reported maximum inclusion rate; the current maximum inclusion rate is 30% for nursery pigs, this study, performed in 2005, utilized DDGS inclusion rates of 10 and 20%.

Powers et al. (2008 & 2006) completed a study in 2006 that included 48 barrows in 8 chambers at Iowa State University. In the study, the animals received increasing amounts of DDGS in their ration (from 0 – 30%) as they progressed through their feeding phases; corn based control diets were also included. The diets were formulated to contain similar amounts of lysine and energy. Manure collection pans were placed under the animal pens and were partially cleaned twice weekly to remove manure and prevent overflow. Air samples were collected from within the animal chambers. The reported results indicated that the NH_3 and H_2S emission rates from the chamber were greater as a result of the DDGS ration. However, they also reported that CH_4 emissions were reduced.

Changes in Manure Characteristics

Limited literature was available related to the effect of DDGS on manure composition in full scale deep pit swine facilities. A study by Donham et al. (1985) (further details provided below) provided some manure composition information from deep pits prior to feeding DDGS, and a study by Martin (2003) (further discussed in the next section titled “Methane Production Potential”) reported manure composition values from a deep pit site not feeding DDGS. Standard deviations for both data sets were quite large, and the only properties comparable between the two data sets were TS, VS, and NH_3-N for grower-finish pigs. However, the average values for TS, VS, and NH_3-N were similar. For TS the average reported values were 10.12 and 9.1%, for VS they were 8.1 and 7.1%, and for NH_3-N they were 5,810 and 5,039 mg/L. For manure composition data relative to DDGS inclusion in swine diets, multiple data points were obtained from an Iowa integrator (Sents, 2009). There are many variables which effect concentration data including temperature which may affect subsequent water usage and wastage in the pit and facility age which may affect solids and nutrient accumulation in the pit over time.

Donham et al. (1985) collected manure samples from 23 Iowa swine confinements with sub-floor pits designed to store manure for six months. At all sites, manure had been in storage for 2-5 months, and manure samples were collected between November and March. The purpose of the study was to determine the chemical and physical properties of liquid manure in the pits relative to conditions necessary for anaerobic digestion. In doing so, they developed a comprehensive dataset of manure characteristics prior to feeding of DDGS. Chemical and physical parameters measured in their study included temperature, pH, bicarbonate alkalinity, volatile acids, ammonia, TS, and VS (Table 5). Donham et al. (1985) reported that in general, low temperatures and the concentration of volatile acids and ammonia were at levels generally deemed inhibitory to anaerobic digestion, and that the level of inhibition was accentuated in grower-finisher and finish operations. The results provided were meant to serve as indicators of anaerobic activity in the deep pits; however, no measurements of CH_4 production or COD and VS reduction were reported to determine what level of anaerobic digestion was actually occurring.

Because no published data was found specifically providing manure composition values from deep pit systems feeding DDGS, an Iowa swine integrator was contacted. Through the Iowa swine integrator (Sents, 2009), manure composition data was obtained from multiple sites and for multiple years. Inclusion rates for DDGS have been steadily increasing for the last several years. Therefore, the yearly data was reflective of multiple DDGS inclusion rates. To reduce variability, only data from finishing pigs utilizing wet/dry feeders was analyzed. While there was variability between the sites, a clear trend was generally present on each site. Though the standard deviations were sometimes large, averaging N, P, K, S, and TS concentrations from seven sites showed a trend of increased manure composition concentration for each parameter with increased DDGS inclusion rate (Figure 1). Samples taken within a single site generally reflected the same trend (Figure 2). This data contradicts the data reported above (Gralapp et al., 2002) as a result of feeding trials. However, the average solids content, which increased from 6 to 8.5% may further substantiate the data reported by Xu et al. (2005) indicating a 10-30% increase in manure volume as a result of increased indigestible fiber due to increased DDGS inclusion.

Table 5. Mean chemical and physical properties of liquid manure collected from 23 Iowa swine confinements with sub-floor pits designed to store manure for six months, table adapted from Donham et al. (1985). Standard deviations are shown in (±).

	No. of Pits	Temp. (°C)	pH	Bicarbonate Alkalinity (mg/L as $CaCO_3$)	Volatile Acids (mg/L as acetic acid)	NH_3-N (mg/L)	TS (%)	VS (%)
Farrow	8	6.6 (± 5.6)	7.12 (± 0.59)	4,565 (± 3,751)	5,070 (± 5,194)	1,392 (± 895)	4.33 (± 4.5)	2.9 (± 3.3)
Farrow-Nursery	2	10 (± 0)	6.45 (± 0.22)	3,675 (± 3,189)	18,250 (± 3,465)	3,840 (± 85)	3.87 (± 0.28)	2.71 (± 0.3)
Nursery-Grower	4	10 (± 5.8)	6.94 (± 0.55)	4,488 (± 5,559)	14,168 (± 12,541)	3,290 (± 1,653)	5.34 (± 2.34)	3.8 (± 2.3)
Grower-Finisher	4	3.8 (± 2.2)	6.86 (± 6.15)	4,110 (± 2,863)	23,175 (± 4,515)	5,810 (± 194)	10.12 (± 1.51)	8.11 (± 1.2)
Finish	5	5.8 (± 5.3)	6.95 (± 0.43)	6,338 (± 5,206)	19,042 (± 11,756)	6,236 (± 2,545)	12.55 (± 3.07)	10.04 (± 2.5)

Methane Production Potential

As previously stated, storage of swine manure in deep pits below slatted floors creates a favorable environment for anaerobic digestion. The CH_4 production potential from manure stored in deep pits has been evaluated at both lab and field scale. Lab scale biochemical CH_4 potential assays have been used to evaluate CH_4 generation potential under optimal conditions from swine manure collected from below slatted floors. At the field scale, a deep pit was monitored for 10 months, and the CH_4 production potential was estimated based on COD reductions. Reported literature verified there was significant potential for CH_4 generation from deep pit storage.

Spajic et al. (2009) performed biochemical CH_4 potential assays on swine manure collected from a finishing operation with a deep pit under slatted floors. At the time manure was collected, the animals were receiving a DDGS ration. The stored deep pit manure had a pH of 7.69 and contained TS, VS, and COD concentrations of 3.73%, 2.59% and 30,200 mg/L respectively. The biochemical CH_4 potential assays provide an estimate of potential CH_4 production under optimal conditions. The data reported by Spajic et al. (2009) indicated CH_4 production from the deep pit manure to be 253.8 mL CH_4/ g VS.

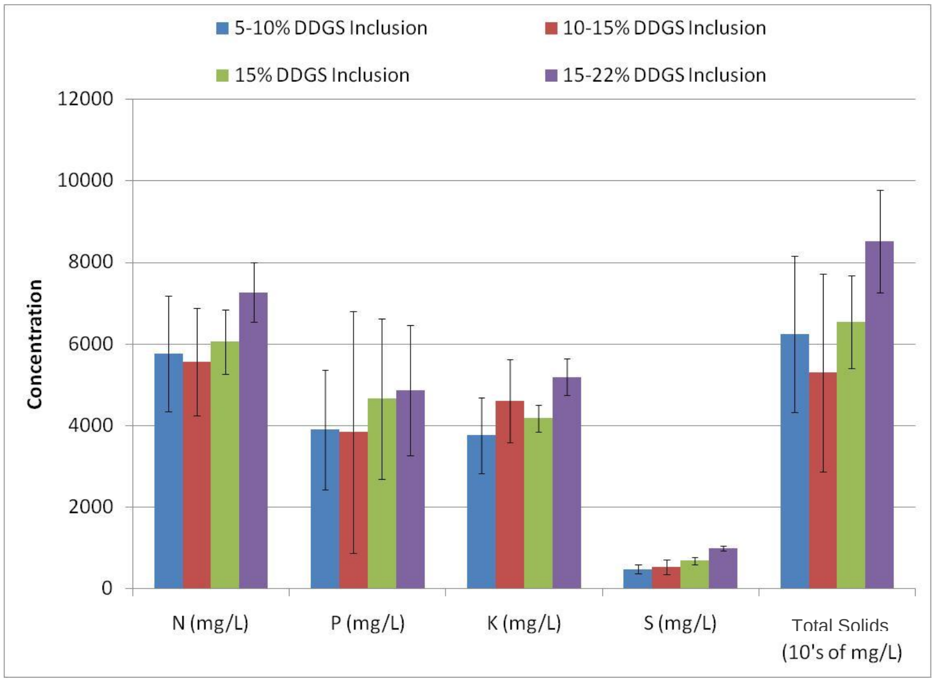

Figure 1. Manure slurry analysis from seven deep pit finishers with wet/dry feeders, samples taken in the fall between 2006 and 2009 (data provided by Sents, 2009).

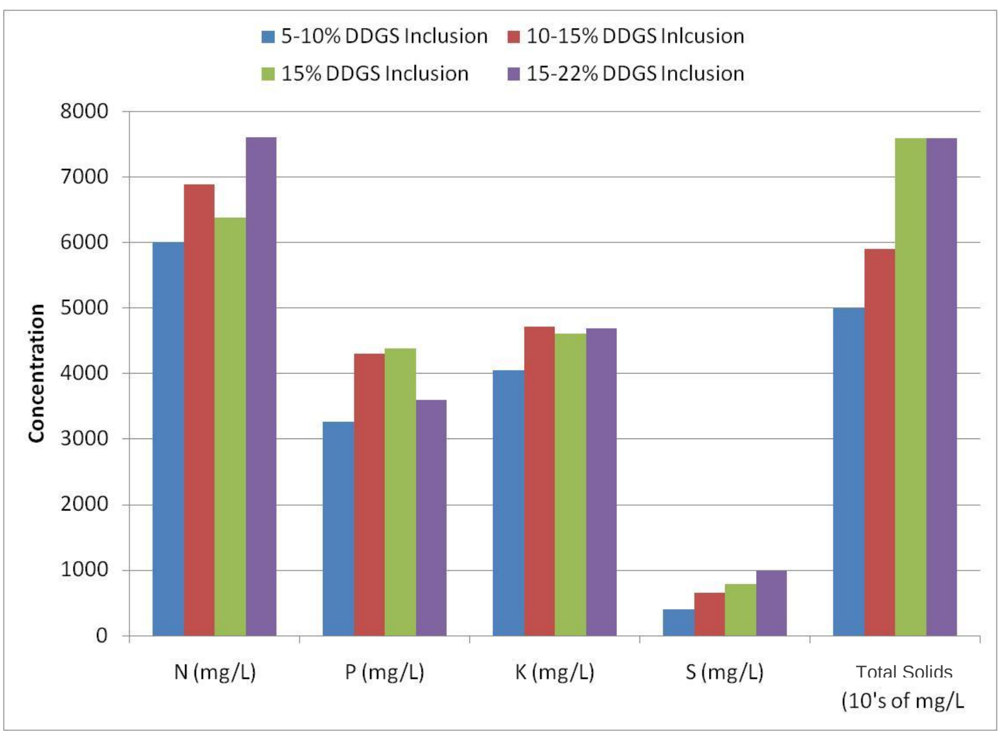

Figure 2. Manure slurry analysis from a deep pit finisher with wet/dry feeders, samples taken in the fall between 2006 and 2009 (data provided by Sents, 2009).

In similar tests performed with manure from a farrow to finish shallow pit scrape system where the animals were receiving a DDGS ration, Wu-Haan (2008) reported potential CH_4 yields of 321 mL CH_4/ g VS. However, because the VS concentration in the scraped manure was so much greater (16.1%) than the VS in the deep pit manure obtained by Spajic et al. (2009) (2.59%), the potential CH_4 generation was much greater as well. This data indicated there was great potential for CH_4 production from swine manure stored in manure pits.

Data was also available indicating considerable amounts of CH_4 could be produced from manure stored within deep pit swine facilities. During 2002, Martin (2003) performed a study to characterize chemical and physical transformations in swine manure accumulated in deep pits under slatted floors and to assess the performance of the system with respect to CH_4, H_2S, and NH_3 emissions. Samples were collected from two groups of feeder pigs finished in a single, 1,000 head deep pit barn between January 2002 and October 2002. During that period, three vertically integrated sub-samples were collected and composited every two weeks. Animals were fed a traditional corn and soybean diet, without DDGS. To determine the reduction of the measured parameters over the 289 day period, the mass of several measured excreted manure properties were calculated using values from the USDA-NRCS Animal Waste Management Handbook. Martin (2003) evaluated the use of the utilized excretion values by comparing them to nitrogen and phosphorus excretion values derived from feed content and nutritional considerations. The derived nitrogen excretion rate was only nominally higher than the estimated rate, and the derived phosphorus excretion rate matched the estimated rate. The mass recovered was based on the volume of materials in the deep pit and the median concentration of the selected properties. No relationship was found between the time of sample collection and concentration of the measured parameters (Martin, 2003). Data from this study is shown in Table 6.

Table 6. Mean properties of liquid manure accumulated in a deep pit under slatted floors and mass excreted and recovered during the finishing of two feeder pit groups, table adapted from Martin et al. (2003).

Parameter	Mean ± Std. Dev. (mg/L)	Median (mg/L)	Mass Excreted (kg)	*Mass Recovered (kg)	Loss (%)
Total Solids	91,778 ± 21,053 (9.1% ± 2.1%)	94,950 (9.5%)			
Total Volatile Solids	71,064 ± 18,173 (7.1% ± 1.8%)	73,485 (7.3%)	118,675	71,243	40
Fixed Solids	20,714 ± 25,821 (2.0% ± 2.6%)	21,307 (2.1%)			
Chemical Oxygen Demand	81,524 ± 25,851	77,450	133,181	75,087	43.6
Total Kjeldahl Nitrogen	6,944 ± 338	6,850	9,450	6,641	29.7
Ammonia Nitrogen	5,039 ± 449	5,100			
Total Phosphorus	2,546 ± 556	2,751	2,527	2,667	+5.5
Orthophosphate Phosphorus	1,399 ± 282	1,350			
Total Sulfur	556 ± 255	550	944	533	43.6
Soluble Sulfide	202 ± 108	163			
pH	7.8 ±0.4	7.6			

*The mass recovered based on median concentration data.

To estimate gaseous emissions, Martin (2003) used calculated losses of VS and COD for CH_4, total sulfur for H_2S, and total Kjeldahl nitrogen for NH_3 emissions during the period samples were collected. For the 289 day period of the study, the total hydrogen sulfide emission was determined to be 284 m^3 (0.98 m^3/ day, 9.8×10^{-4} m^3/ animal·day). Methane emissions occurring over the 10 month period were estimated at 20,381 m^3 (70.5 m^3 per day, 0.705 m^3/animal·day). Martin (2003) compared VS and COD losses from the deep pit to that of a mesophilic anaerobic digester operating on swine manure. He concluded that the system was functioning similarly to the mesophilic anaerobic digester. The deep pit achieved a 43.6% and 40% reduction COD and VS; comparatively, the mesophilic anaerobic digester was achieving 68.8 and 64% reductions in COD and VS. That means the deep pit was operating near 64% of the performance of a designed anaerobic digester. Loss of organic matter is achieved through reduction of organic carbon to CH_4 or intermediate volatile organic compounds that desorb from solution (Martin, 2003). In the deep pit system reported here, pH (7.8) and temperature (~20°C) suggested an environment very favorable to anaerobic digestion; therefore Martin (2003) assumed the anaerobic process would be effective and only a nominal loss of organic matter as intermediate volatile organic compounds would occur.

Other Possible Factors

During the 2009 production cycle, temperatures were cooler than normal in the Midwestern United States. Correspondence with an Iowa swine integrator (Sents, 2009) indicated that water consumption was lower at their finishing operations in 2009 and that some manure chemical and physical properties were higher because of reduced dilution water in the system. Based on information obtained in the literature review, increased manure composition concentrations could have increased flammable gas production or increased the likely hood of foaming due to increased organic loading in the deep pit systems.

Also in relation to foaming, choice of cleanser used within the facility could have the potential to increase or decrease foaming in the deep pit. However, available circumstantial information suggests that foaming and fires occurred whether systems are washed with detergent, disinfectant, or water. Detergents are a class of surfactants, and as previously stated in the section on foaming, surfactants are surface active compounds. Information reported by Schmidt (1997) relative to cleaning agents for food processing operations may provide information helpful in deep pit systems. Schmidt (1997) stated detergents contain both hydrophobic and hydrophilic fractions and promote cleaning by emulsification, penetration, spreading, foaming, and wetting. Detergents can be ionic surfactants or non-ionic surfactants. Ionic surfactants are water soluble and are generally characterized by their high foaming ability. Non-ionic surfactants do not dissociate when dissolved in water, and they have a broad range of properties depending on their hydrophilic/hydrophobic balance which can also be affected by temperature (Schmidt, 1997). As their temperature increases, the hydrophobic character and solubility decreases. At their lowest solubility, they act as defoamers.

Possible Mitigation/Management Options

Gases resulting from anaerobic decomposition of animal manure are the likely source of barn fires. Specifically which flammable gas is the primary fuel source (CH_4, H_2S, PH_3, or a combination of the three) has not been specifically addressed in published literature. A review of the literature indicated that the only flammable gas reported at concentrations above the lower explosive limit within deep pit systems was methane. Additionally, while evidence was somewhat circumstantial (foam was present at several of the deep pit fires and CH_4 content within the foam from two of the barn fires sites was between 10 and 73%), foam was likely a significant contributor to the elevated gas levels within the facilities when they were agitated or otherwise disturbed by an action that resulted in foam breakage. Methane is lighter than air; once released from the foam, high levels could easily dissipate to explosive levels between 5 and 15%. Hydrogen sulfide and phosphine are both heavier than air; therefore when released from the foam, they could easily concentrate in pit head space and just above slatted floors.

Based on the assumption that foam traps methane formed during manure storage in deep pit swine systems, and when released can be ignited, one management alternative would be to alter the source yielding foam development within deep pits. However, as described above in the literature, no information was found related to foaming in stored manures. Information about reasons for foaming in anaerobic sludge treatment systems and digesters is still somewhat theoretical and foam production is likely the result of multiple factors. Feeding DDGS rations, reduced water use during the cool 2009 summer, and choice of barn cleanser may contribute to the foam production. There was evidence that DDGS increased excreted manure volumes due to higher levels of indigestible fiber in the feed, and decreased water usage by the animals resulted in more concentrated chemical and physical parameters in the manure.

Therefore, currently the best management practices to reduce the risk of barn flash fires and explosions are to manage and reduce flammable gas concentrations and to remove any ignition sources when foam is removed from or agitated in the pits. The following section provides some information about managing gas production with ventilation and reducing foam with antifoaming agents.

Management Changes to Reduce Risk

Managing Gas Concentrations

Patni and Clarke (2003) measured H_2S concentrations before, during, and after sub-floor slurry pit agitation and mixing. Measurements were made under normal operation and ventilation conditions. They determined pit exhaust fans to be effective in reducing H_2S concentrations above the slats in the barns to below danger levels. Pit fan H_2S concentrations were generally higher than corresponding in-barn air sample concentrations. Pit fan ventilation rates at the sites visited were 227-368 m^3/min (8,000-13,000 ft^3/min). In two cases, in-barn H_2S concentrations were higher in the barn than in the pit exhaust air. In one barn, operation of the barn exhaust fans at the same time as the pit exhaust fans resulted in higher in barn H_2S as compared to when the barn exhaust fans were off. At another barn, the barn exhaust fans were larger than the pit exhaust fans, and H_2S concentrations tended to be higher in the barn at this facility. Additionally, sites 1, 2, and 10 (see Table 3) had low maximum and average in barn H_2S concentrations during normal pit exhaust fan operation. However, site 9 (see Table 3), with similar conditions had higher in barn concentrations compared to the pit exhaust. The authors believe the effect was related to the limited pit head space due to the pit being full of manure. Patni and Clarke (2003) recommended the following to reduce manure gas hazards in barns with sub-floor manure storage:

- Well functioning, properly sized and located pit exhaust fans are valuable to control manure gas. Installation of a warning device to indicate pit fan failure would be useful during periods of unattended agitation and mixing.
- For barns containing both pit and exhaust fans, only operate the pit exhaust fans during agitation. The in-barn ventilation fans can draw gases through the slats and into the barn space. This is critical when barn ventilation fans are more powerful than pit exhaust fans.
- Maintain adequate head space in the sub-floor pit head space to maintain effective operation of the pit exhaust fans.

Zhao et al. (2005) measured in-house odor and gas levels in a deep-pit wean-to-finish operation that had both house ventilation and deep-pit exhaust fans. Multiple samples were collected throughout the house; samples within the pens were collected at pig head height, and samples in the center alley were collected at human head height. The air sample H_2S concentrations increased with the proximity of the sample location to the tunnel exhaust fans. Near the exhaust fans, the concentration increased from 2 to 20 x's, with the greatest difference being from ~50 to 1000 ppb. Zhao et al. (2005) indicated that in the vicinity of the exhaust fans, more gases were pulled up from the pit.

Mitigation Options to Suppress or Reduce Sources

Gaseous Emission Mitigation

Donham et al. (1985) listed three alternatives to improving in barn environments above manure storage pits. These included; 1) aerobically treat manure stored in pits using aeration systems, 2) improve conditions for more rapid and complete anaerobic digestion, or 3) completely stop biological activity (and thus gas production). The authors recognized that aeration systems would have high energy and maintenance costs, controlled anaerobic digestion would require continued investigation, and that preventing biological activity would require altering pH or adding chemical to produce conditions toxic to anaerobic micro-organisms.

Foam Mitigation

Most of the literature related to foam control is relative to municipal wastewater treatment and the bioprocessing industry. Limited literature was found related to foam control in manures. In manure aeration systems, Cumby (1987) suggested minimizing the use of detergents and disinfectants to provide a degree of prevention. Additionally, for foaming in aerated manure systems, Cumby (1987) suggested two groups of foam control methods, mechanical and chemical. In regards to chemical methods, Cumby (1987) suggested insoluble oils or similar substances could control foaming because they are insoluble in water and have a lower surface tension than the solution. This may seem contradictory, but other literature suggests that by having a lower surface tension than the foaming solution, antifoam molecules absorb to the solution interface and form a low viscosity film which helps prevent foaming (Etoc et al., 2006). As stated, additives would replace the surface active agents causing the foam, and could be applicable at relatively low concentrations (Cumby, 1987). Wheatland and Borne (1970) reported achieving satisfactory foam control in pig slurry using antifoaming oil (limited information was provided), but van Niekerk et al. (1987) reported that reports of antifoam use had not been favorable (again, limited information was provided). Cumby (1987) also noted that antifoaming oils could be a risk to soil pollution when the resulting manure was spread on agricultural land, and that it should be used occasionally and not as a regular measure. In manure aeration systems, mechanical foam control devices involve destruction of foam by shearing. Foam control devices generally force liquid and foam through narrow slits or holes, therefore Cumby (1987) indicated that devices made for other industries with thinner liquids may not work well with manures.

Literature was available relative to foam control for anaerobic bioprocesses and anaerobic sludge digesters, but most of the authors agreed that theories behind foam collapse were not completely understood making it hard to find single antifoaming solutions that work for every situation (Barber, 2005; Vardar-Sukan, 1988). Foam mitigation literature for non-manure systems has been broken down into three categories; chemical, mechanical, and biological. Chemical methods involve the addition of amendments to the fluid creating the foam; they work by altering the liquid and foam interface of the fluid and by reducing liquid viscosity (Barber, 2005). Mechanical methods involve foam destruction by shearing. Foam control devices generally force liquid and foam through narrow slits or holes (Barber, 2005; Cumby, 1987); ultrasonication has also been used (Barber, 2005). Biological methods include introducing microorganisms to the foaming fluid that control or eliminate the filamentous foam causing bacteria such as *Norcardia* (Barber, 2005). However, as previously noted, the filamentous foam causing bacteria were generally thought to be residuals of the aerobic activated sludge plants (Ganidi et al., 2009), therefore biological methods were not discussed here.

Barber (2005) reported the advantages of chemical foam mitigation systems to include their use as a preventative measure and ability to apply by multiple methods. Disadvantages were reported to include potential mass transfer issues (i.e can be difficult to distribute within the stored manure), potential toxicity issues (defoamer may be toxic to anaerobic systems), effluent contamination, and adverse effects for downstream use of the material. Barber (2005) reported that there were over 700 commercially available antifoaming agents. Etoc et al. (2006) divided antifoams into two categories, soluble or insoluble oils (Etoc et al., 2006). Soluble oil antifoams were reported to generally be based on surfactants containing polyethyleneoxyde or polypropylene oxide compounds that have a lower surface tension than the foaming liquid (Etoc et al., 2006). The antifoam molecules adsorb to the interface and form a low viscosity film to prevent foam formation. The insoluble oil antifoams such as polydimethylsiloxane were usually formulated with hydrophobic particles to aid the antifoam droplet in entering the solution surface (Etoc et al., 2006). Essential features of antifoaming agents were that they have a low viscosity and the facility to spread rapidly on foamy surfaces.

Because foam collapse and utilization of antifoaming characteristics has not been fully understood (Barber, 2005), the best way to determine which antifoaming agent works for a specific liquid and foam type is to conduct performance testing on the foam in question. Vardar-Sukan (1988) tested the ability of multiple natural oils to act as antifoaming agents in bioprocess systems. Their work showed that foam suppression was a result of the balance between various surface active agents including the amended anti-foam. Some of the natural oils tested were capable of destroying the foam in one of the bioprocesses, but the same oil acted as a foam stabilizer in the other. Vardar-Sukan (1988) concluded that it was imperative to account for variations in material compositions when choosing the most suitable antifoaming agent, and that antifoams working for one set of materials may not work for another. Test procedures to evaluate the performance of antifoaming agents have been developed and are available in the literature (Etoc et al., 2006; Vardar-Sukan, 1988).

Barber (2005) reported advantages of mechanical antifoaming systems to include that they are non-contaminating and non-toxic to system microbes; disadvantages included complex design, responsive instead of preventative measures, and limited effectiveness. Mechanical devices for antifoaming include revolving disks, paddles and stirrers, injectors and orifices, centrifuges and cyclones, and other destructive techniques such as ultrasound (Barber, 2005). Critical speed and power consumption are considered to be significant factors when selecting a mechanical antifoaming system. For ultrasonic systems, amplitude was an important factor influencing foam collapse; with higher frequencies being more effective in foam destruction.

Understanding the specific cause and reducing the likelihood of foaming is also worth considering. Ganidi et al. (2009) concluded their review by noting that foaming likely occurred when the concentration of surface active agents in an anaerobic system exceeded the concentration necessary to achieve the agents critical micelle concentration (the concentration at which molecules cluster and begin to reduce the liquid surface tension). They suggested that determination and control of surface active agent critical micelle concentrations were crucial to foaming prevention and cost-effective foam control. In other words, for deep pit manure systems, to select the most appropriate antifoaming agent, the likely cause of the foam must first be determined.

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