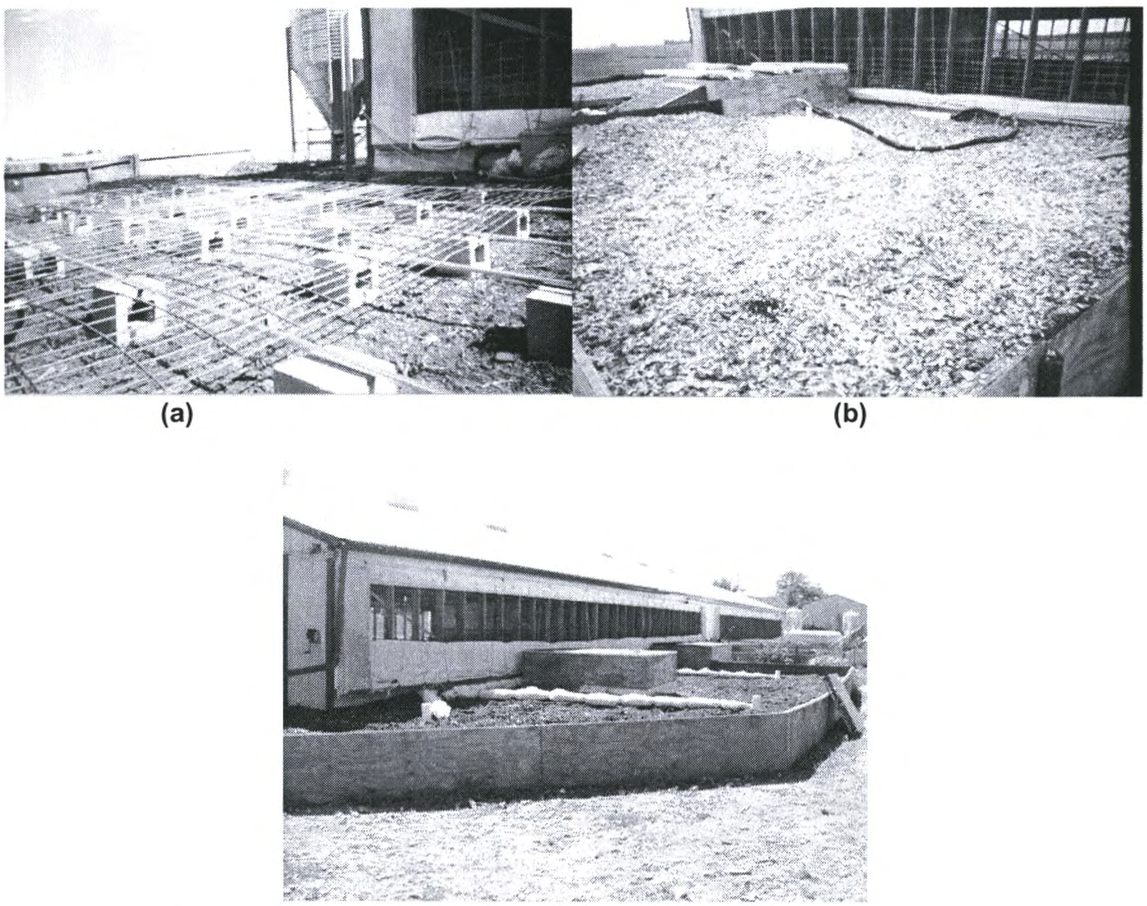
108 m^2 (1,162 ft^2). The target biofilter parameters were adjusted to accommodate on-site space limitations. In total, 88 m^2 (947 ft^2) of surface area was available for this project and with a selected depth of 25 cm (10 in), resulted in a final minimum residence time of 3.25 sec.

The biofilter media chosen was standard oak hardwood chips with each chip approximately 5 cm square (2 in). This media, free of fines, was purchased from a local supplier of landscaping products. This media was selected based on in-house testing for moisture holding capacity (see Chen et al., 2008). The chips used had a porosity of 56±0.5% determined using the bucket test method (Rosen et al., 2000).

The biofilter plenum consisted of a series of 20 cm (8 in) square concrete blocks, electrical conduit used as support rods, 10 cm square (4 in) wire panels, and two-layers of 1.3 cm (0.5 in) fiberglass mesh. The plenum and completed biofilter is shown in figure 3. The biofilter was watered on a timer for two hours each day (06:00-07:00 and 22:00-23:00). The application rate averaged 4.5 liters/day-pig (1.2 gal/day-pig).



(a) (b)

(c)

Figure 3. Biofilter plenum (a), wood chip media (b), and completed biofilter (c).

The key concept in partial biofiltration using the CMVR is to suppress curtain activity during the most stable hot weather periods and to transfer the ventilation needs to the biofilter fans. From this research project, the fan percentage of the total airflow rate delivery was recorded between the CTL and TRT rooms. Considering the consecutive time period between 20:00 and 07:00, the percentage of total airflow delivered by fans during this time period was 67% for the TRT room and 49% for the CTL room. This implies that on average 67% of the total emitted air from the TRT room was being biofiltered during potentially the most stable periods of the day. Figure 4 shows a histogram of the TRT and CTL room fan percentage of the total airflow for the entire month of July 2006 for the consecutive time periods between 20:00 and 07:00. The CTL room fan percentage of total was centered in the 30-50% range where the TRT room fan percentage of total was in the 55-100% range.

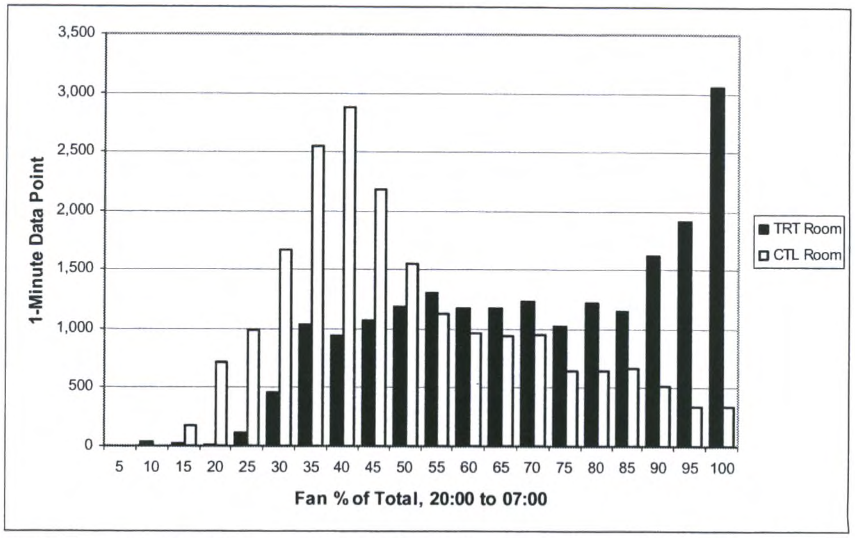


Figure 4. Percent of total room airflow delivered by fans between the CTL and TRT rooms.

Based on the experiences from this research project, some highlighted areas are noted below;

Biofilter Media: Very careful attention to biofilter media composition needs to occur. The media selected must be screened for fines. If compost is mixed with wood chips, the fraction of compost needs to adhere strictly to the recommendations given in past documents on biofilter design (Nicolai and Janni, 2001). This research project showed that a biofilter consisting strictly of wood chips is an effective media for biofiltration provided adequate moisture is applied and retained.

Biofilter Plenum Design: It has been a common practice to use stacked wood-pallets for constructing horizontal-bed biofilter plenums. A modified approach using concrete blocks, galvanized support bars, hog panel, and mesh proved to work well. Caution in the selection of mesh material needs to be considered. Two-layers of fiberglass mesh (1.3 cm square) were used and after two years of operation it has been observed that wood-chip fines have settled causing significant airflow obstruction. The mesh used should be just small enough to prevent the original wood chip material from passing into the plenum.

Biofilter Fan Transition: It is extremely important that the transition area from the fan to the biofilter plenum be designed in such a manner that an easy and restriction-free zone exists into the biofilter. The transition area that was designed for this research project used a velocity criterion of 9,150 $m^3/h\text{-}m^2$ (500 $ft^3/min\text{-}ft^2$). The recommendation would be to maintain this transition area at or below this level for all locations prior to the biofilter plenum. Failure to provide adequate distribution area into the biofilter plenum will result in excessive operating static pressures.

Partial Biofiltration: The results from this research support the concept of partial biofiltration. The research data collected for this project demonstrated that a significant portion of the evening hours was fan ventilated and scrubbed *via* biofiltration at a maximum biofilter fan rate of 81 $m^3/h\text{-pig}$ (48 $ft^3/min\text{-pig}$). This rate is roughly 50% of the total fan capacity designed in swine finishing facilities.

Barn Modifications: It is important that secondary inlets into the attic space and primary inlets into the occupied room space be sized to design specifications to avoid excessive operating static pressure. With the added restriction of a biofilter, the ventilation system needs to minimize all other air restriction points in the ventilation process beyond the inlet distribution system itself. Ultimately, the biofilter installed can not negatively affect the ventilation needs of the animals

Technology Summary:

The technology summarized in this paper used a biofilter to treat a critical minimum amount of ventilation air in a hybrid-ventilated deep-pit swine finisher. The logic of the method described is to provide just enough ventilation air mitigation to suppress curtain opening during predominantly stable summer night-time conditions when the tendency for odor transport is greatest. The method discussed and tested had an estimated capital and labor cost of $22.53/pig-space and an added biofilter fan operational cost of $0.42/pig.

Additional Resources:

More specific details related to the research project summarized in this paper can be found in Hoff et al. (2008). Biofilter design considerations can be found in Nicolai and Janni (1999), Janni et al. (2001), and Nicolai et al. (2002).

Acknowledgments:

The authors would like to thank Mr. Greg Carlson, Stratford Iowa, for allowing this research project to be conducted at his production site. The support staff consisting of Brian Zelle, Michael Crevalt, David Smith, and Aaron Smith spent many hours working through design changes and site inspections required to make this research project possible and there support is very much appreciated. The authors would like to thank the Iowa Pork Producers Association and the USDA-Special Grants program for making this research project possible with their generous funding support.

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As published in the proceedings of:
MITIGATING AIR EMISSIONS FROM ANIMAL FEEDING OPERATIONS CONFERENCE
Iowa State University Extension
Iowa State University College of Agriculture and Life Sciences
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Iowa Pork Producers Association
U.S. Pork Center of Excellence

Biofiltration-Mitigation Odor and Gas Emissions from Animal Operations

R. Nicolai[1], K. Janni[2], and D. Schmidt[2]
South Dakota State University[1], University of Minnesota[2]

Species: Swine, Dairy
Use Area: Animal Housing
Technology Category: Biofilter
Air Mitigated Pollutants: Hydrogen Sulfide, Ammonia, Methane, Volatile Organic Compounds, Odors

Description:

A biofilter is simply a porous layer of organic material, typically wood chips or a mixture of compost and wood chips, that supports a population of microbes. Odorous building exhaust air is forced through this material and is converted by the microbes to carbon dioxide and water. The compounds in the air are transferred to a biofilm that grows on the filter material.

Biofiltration can reduce odor and hydrogen sulfide (H_2S) emissions by as much as 95% and ammonia by 65%. (Sun et al., 2000; Nicolai et al., 2006)The method has been used in industry for many years and was recently adapted for use in livestock and poultry systems. Biofilters work in mechanically ventilated buildings or on the pit fans of naturally ventilated buildings. Biofilters can also treat air vented from covered manure storage units.

Key factors influencing biofilter performance are the amount of time the odorous air spends in the biofilter and the moisture content of the filter material. Design issues include the amount of air treated, sizing of the biofilter bed, selecting fans to push the air through the biofilter, choosing biofilter media, moisture control, operation and management, and cost of construction and operation.

Mitigation Mechanism:

The odorous air exhausted by a fan from the building is uniformly distributed beneath the biofilter media then passes through a bed packed with organic carrier materials, i.e. media consisting of wood chips and/or compost. The odorous and gaseous compounds in the air are transferred to a biofilm that surrounds media particles in the bed where the microorganisms break down the compounds. The compounds provide the nutrients necessary for microorganism growth. Several processes take place in the biofilter system to remove odorous compounds (Jordening and Winter, 2005). They include:

1. Transferring the odorous compounds in the air to the liquid phase surrounding each particle of the organic material.
2. Migration of the odorous compounds from the bulk liquid phase to the biologically active phase or biofilm that grows on the filter material.
3. Degradation of the pollutant by the microbes takes place in the biofilm where the biodegradable gas is oxidized into carbon dioxide, water, mineral salts, and biomass (more microorganisms).
4. The end products from the microbes migrate back through the liquid phase and emitted into the air phase. The cleaned exhaust air then leaves the biofilter.

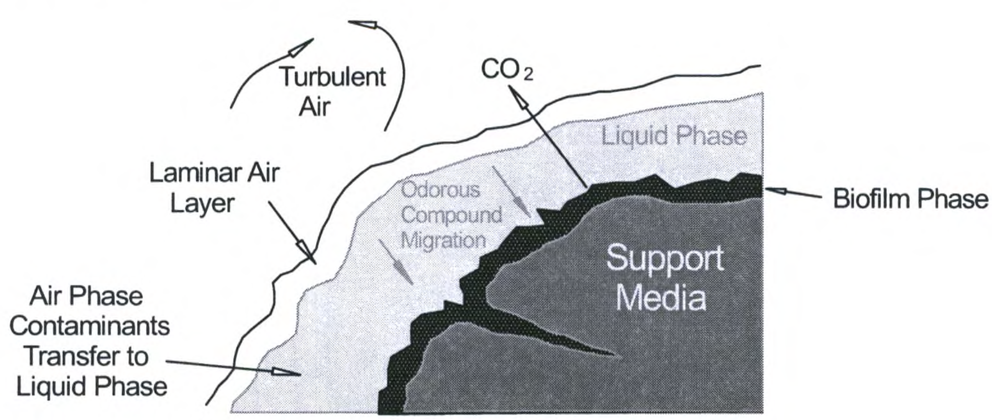

Figure 1 Biofilter Process

An important control parameter is the moisture content of the overall carrier material, which must be between 40% and 60% (wet basis). To avoid microorganism dehydration, the organic carrier material requires moisture application.

Biofilters are effective in reducing odorous compounds, volatile organic compounds, hydrogen sulfide, ammonia, methane, and volatile fatty acids. Odor and hydrogen sulfide emissions can be reduced from livestock facilities by 85% to 95% while ammonia and methane may be 50% to 90% depending on operating parameters (Nicolai and Janni, 2000; Sun et al., 2000; Nicolai et al., 2006; Nicolai and Thaler, 2007).

Applicability:

The air to be treated must be controlled in a duct system and pressurized to pass through the biofilter media. Therefore biofilters are suited to mechanically ventilated applications, such as power ventilated swine barns, dairy manure collection pits that are power ventilated, covered manure storage structures that are power ventilated.

Two configurations of biofilters are being used to treat exhaust air from swine buildings. They are a horizontal bed (figure 2) and a vertical bed (figure 3). Horizontal biofilters on swine barns have been shown to reduce odors from exhaust fans and are less expensive than vertical (Nicolai and Janni, 2000, Nicolai and Thaler, 2007). The media bed is typically 12 to 18 inches deep. Horizontal deep-bed biofilters are an option when space is limited and centrifugal fans can be used.

But in some situations, there is not enough area to construct a large horizontal biofilter designed for large airflows. Vertical biofilters offer an advantage because they utilize less surface area than a horizontal for the same airflow. The media in a vertical biofilter is placed between two support structures in which the treated air passes through horizontally.

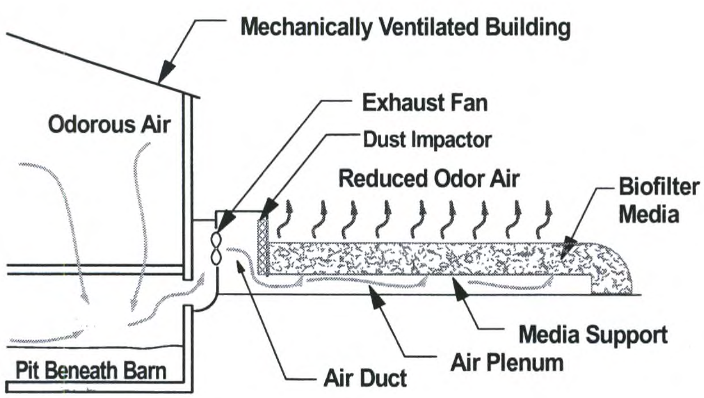

Figure 2 Horizontal Biofilter

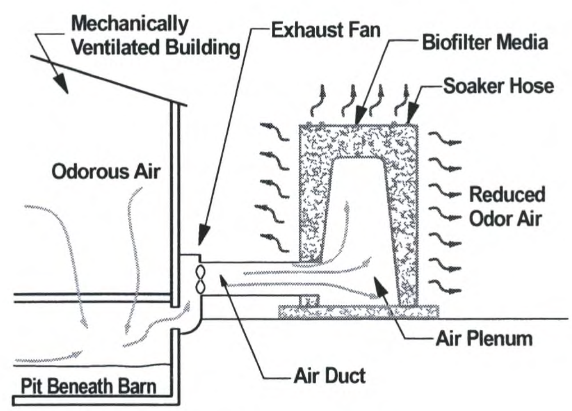

Figure 3 Vertical Biofilter

Figures 2 and 3 illustrates elements of an open-bed biofilter. They are:

- a mechanically ventilated space with biodegradable gaseous emissions;
- an air handling system to move the odorous exhaust air from the building or manure storage through the biofilter;
- an air plenum to distribute the exhaust air evenly beneath the biofilter media;
- a structure to support the media above the air plenum;
- porous biofilter media to act as a surface for microorganisms to live on, a source of some nutrients, and as a structure where moisture can be applied, retained, and available to the microorganisms.

Limitations:

Naturally Ventilated Buildings

Biofilters are only effective when there is a captured air stream. This air stream is typically the fan exhaust from mechanically ventilated buildings or the exhaust from nonporous covered manure storage. The air emissions through the sidewall of a naturally ventilated building typically cannot make use of a biofilter.

However, some naturally ventilated buildings use some mechanical ventilation in combination with natural ventilation. The mechanical portions of the ventilation may include pit fan exhaust and sidewall fans that operate to provide minimum ventilation in the winter. For these types of facilities it is possible to install biofilters on the exhaust fans.

The amount of odor reduction achieved in naturally ventilated barns is variable. During the cool months when most of the ventilation air passes through the exhaust fans and subsequently the biofilter, odor reduction is similar to that of mechanically ventilated buildings, or approximately 80-95%. However, during the summer months the primary means of providing air exchange through the barn is by natural ventilation (curtains and/or ridge vents). During these times, the odor reduction provided by a biofilter on the pit and wall fans is less, depending on the percentage total ventilation air treated. However, during warm weather the much greater natural ventilation air exchange rate through the barn leads to lower gas and odor concentrations.

Cost:

Costs to install a biofilter include the cost of the materials—fans, media, ductwork, plenum and labor. Typically, cost for new horizontal biofilter on mechanically ventilated buildings will be between $150 and $250 per 1,700 m^3/hr (1,000 cfm). A vertical biofilter is approximately 1.5 times the cost of a horizontal biofilter.

Annual operation/maintenance of the biofilter is estimated to be $5-$10 per 1,700 m^3/hr (1,000 cfm). This includes the increase in electrical costs for fans to push the air through the biofilter and the cost of replacing the media after 5 years.

Both capital costs and operation and maintenance costs are quite variable. High-cost situations are those where biofilters are retrofit on naturally ventilated buildings to filter air from pit fans or from additionally installed fans for mild weather ventilation.

Implementation:

Biofilter design

Biofilter designs are based on the volumetric flow rate of air to be treated, media characteristics, biofilter size (area) constraints, and cost. These parameters all play a role in the efficient cleaning in economical operation of the biofilter:

Airflow rate – Biofilters should be sized to treat the maximum ventilation rate—typically the warm weather rate—of the building. This ventilation rate is dependent on the type, size, and number of animals in the building. Proper ventilation design procedures can be found in MWPS-32, *Ventilation systems for livestock housing*. To achieve pit gas odor reduction through biofiltration, up-drafting through the slatted floor should be eliminated when the curtains are open. For example, in a curtain-sided swine finishing barn, a minimum ventilation rate of 75 to 85 m^3/hr (45 to50 cfm) per pig is recommended to achieve complete down-draft when the curtains are opened.

Biofilters treating air from a manure storage unit will treat a lesser volume of air with a higher concentration of odorous gases. Typical airflow rates from covered manure storage are 0.01 cfm per square foot of surface area.

Media characteristics – For a biofilter to operate efficiently, the media must provide a suitable environment for microbial growth and maintain a high porosity to allow air to flow easily. Critical properties of media material include (1) porosity, (2) moisture holding capacity, (3) nutrient content, and (4) slow decomposition.

In a biofilter, the relationship between airflow rate and static pressure depends on the type of media and media depth. Figure 4 shows this relation between Unit Airflow Rate (UAR, the amount of airflow per square foot of biofilter surface) and Unit Pressure Drop (UPD, the static pressure drop per foot of biofilter media depth) for a variety of materials tested in the lab. The lines shown are for media with different percent voids. Percent void is a measure of the amount of open pore space in the media.

As airflow rate increases, the pressure drop through the media increases i.e. as airflow increases it takes more pressure to push the air through the media. Also, as porosity increases, the pressure drop decreases. This porosity is both a function of the original media, compaction of the media, and media moisture content.

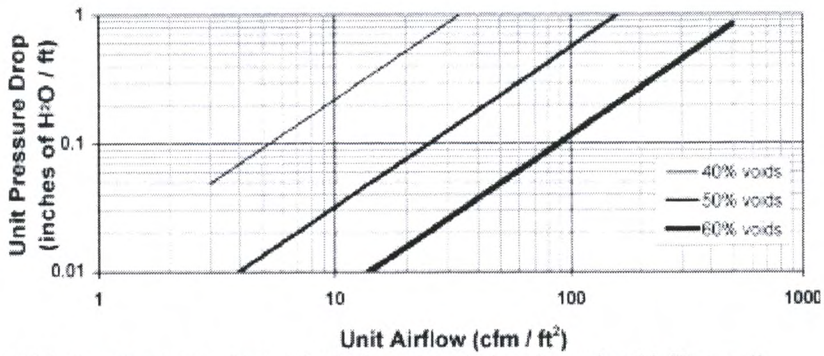

Figure 4 Media unit pressure drop and unit flow rate relations for various biofilter media.

To decrease this pressure drop and increase airflow, the media depth can be decreased. If this is not possible, the biofilter area must be increased, thus increasing the EBCT. Increasing the EBCT means a better filter efficiency, a lower pressure drop, more biofilter media, and a larger biofilter area. Building a larger biofilter can be justified due to the less powerful fans needed and the reduced operating cost of these fans.

Porosity can also be affected by age of the media. Over time the media decomposes and settles which reduces pore space. Any activity that causes compaction, such as walking on the media, also will reduce pore space.

Retention or Empty Bed Contact Time (EBCT) – Retention time is the amount of time that the air is in contact with the biofilter media. A longer retention time gives the biofilter a longer time for the odorous gases to be absorbed into the liquid phase resulting in more odor reduction but will also require a larger area for the biofilter. Retention time depends on the specific gas (or gases) being treated and concentration of the gas (gases). EBCT is determined by dividing the volume of the media (m^3 or ft^3) by the airflow rate (m^3/s or ft^3/s).

Maintenance

Attention is needed in four areas—moisture content, weed control, rodent control, and assessing pressure drop. None of these management issues takes significant amounts of time, but all are important for proper biofilter operation.

Moisture content – Biofilter moisture management requires some on-the-job training. Typically, no moisture measurements are needed. Rather, the feel and look of the filter material will be indicators of too much or too little water. During cold weather the media moisture content is fairly constant (from heated exhaust air) and remains at approximately 50%. However, in the summer a media watering system is needed. A standard lawn sprinkling system is fairly effective. However, because the media dries from the bottom and is watered from the top, it is necessary to dig down into the media to check moisture content. Dampness should be felt one-half to three-quarters of the way down through the depth of the media. If dampness is felt throughout the depth of the media, then the watering system is providing too much water. If, however, only the top few inches are damp then the water needs to be increased. Often, watering is done at night for one or two hours to reduce evaporation losses.

Water can be applied through surface irrigation i.e. sprinkling the top of the media. On a horizontal biofilter sprinkling provides direct control but can lead to 'fingered' downward flow. A finer droplet size tends to improve water distribution. Excess moisture is generally not a problem because the additional moisture drains through the media or evaporates due to the constant airflow through the biofilter. For a vertical biofilter configuration, a soaker hoses on the top surface allow the water to be evenly distributed.

Weeds – Weed growth on the biofilter surface can reduce efficiency by causing air channeling and limiting oxygen exchange. Roots can contribute to plugging of biofilter pores. Weeds on a biofilter also reduce the aesthetic appearance of the livestock site. A systemic herbicide or some other means should be used.

Rodents – A good rodent control program is essential. Mice and rats burrow through the warm media during the cold winter months, causing channeling and poor treatment. Rabbits, woodchucks, and badgers have been suspected of burrowing through and nesting in biofilters. Fortunately, most livestock and poultry operations currently have a good rodent control program. These programs are not very expensive.

Assessment of pressure drop – Over time the degradation of the media material, dust buildup in the media, and media settling will cause the pressure drop across the media to increase. As pressure drop increases the amount of air moved by the ventilation fans decreases, eventually resulting in poor building ventilation. The type of biofilter media and the dustiness of the exhaust air will both affect the length of time before the media plugs and the pressure drops become excessive.

Unfortunately, no long-term studies have been conducted to determine just how long this will take, but it is estimated that most biofilters will last 5 to 10 years or more. Poor building ventilation at maximum ventilation rates will likely be the first sign of biofilter plugging. A manometer can be used to check the pressure drop across the biofilter. Depending on the design of the biofilter and the ventilation fans selected, an increase in the pressure drop across the media of over 50% of the design pressure drop indicate the need to replace the media. The maximum pressure drop must be measured at maximum ventilation rates.

Technology Summary:

Biological treatment fills the need for an economical means of treating low concentration odorous and other compounds coming from building emissions. The concept of biological air treatment involves bringing the air in close contact with a water phase that contain active microorganism.

The need to keep biofilters moist is a significant design consideration. Large amounts of air pass through biofilters causing a slow but steady drying that eventually disrupts the microbial activity.

The Technology Summary is meant to be a basic summary of your entire paper including Mitigation Mechanism, Applicability, Limitations, and Economics, as well as other important points made in your paper.

Additional Resources:

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As published in the proceedings of:
MITIGATING AIR EMISSIONS FROM ANIMAL FEEDING OPERATIONS CONFERENCE
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Iowa State University College of Agriculture and Life Sciences
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Significant Odor Reduction from a Highly Efficient Micro-ecosystem™ based on Biofiltration

R. Treloar and R. Treloar
Odor Cell Technologies LLC

Species: Swine
Use Area: Animal Housing
Technology Category: Biofilter
Air Mitigated Pollutants: Ammonia, Hydrogen Sulfide, Particulate matter, Odor

Description:

Swine facilities produce an organic by-product (manure) that has become increasingly vital to crop production and nutrient management. This organic liquid is usually stored in a pit directly underneath the housing facility or adjacent to the facility in a lagoon or formed structure. The storage and subsequent breakdown of this material causes gases and odorous particulate matter to be released into the ambient air affecting air quality in and around these facilities (Lee et al., 2006). Exhaust fans are most often employed to remove these gases from underneath a housing facility. Odorous emissions are a composite of organic compounds, ammonia, hydrogen sulfide, and particulates (Wood, S.L., et al., 2001). Research findings by Green et al. (2005) have demonstrated significant reduction in hydrogen sulfide and ammonia emissions utilizing biofiltration.

Odor Cell Technologies LLC, (OCT) has developed hybrid odor cells that synergistically combine the principles of biofiltration with technology that maintains optimal environmental conditions creating a micro-ecosystem within the cells.
This technology uses above ground cells which contain an organic media, pine bark, to establish this aerobic micro-ecosystem. Pockets of anaerobic activity that are inherent in traditional biofilters are not a factor in the odor cells (Cundiff et al., 2003). These cells attach to pit exhaust fans individually which allows for flexibility based on actual run-time calculations (Figure 1). The cells are connected to a water source where hydration cycles can be programmed through the use of timers and rain sensors (Figure 2). Maintenance and physical inspection can be easily done by adding media to the cell and lifting the top panel to observe the point of contact within the capture chamber.

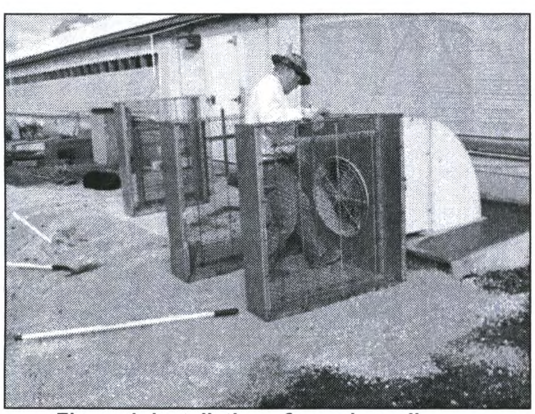

Figure 1. Installation of an odor cell

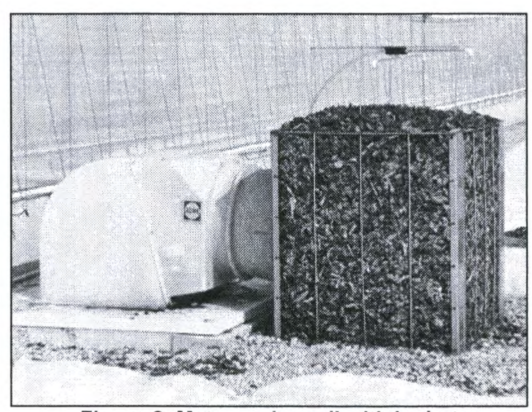

Figure 2. Mature odor cell with hydrator

In addition to reducing odorous emissions, other benefits of the technology are:

- Capture of particulate matter which reduces the transfer distance of odor
- Improved air quality within a rural setting
- Environmentally friendly filtering medium
- Aesthetically appealing and visible odor reducing technology
- Addresses a wide variety of ventilation emissions
- Requires no upgrades to existing ventilation fans
- No shutters required on minimum ventilation fans
- No static pressure variability on fans from ambient winds/snow
- Microbial conditions easily monitored and maintained

Mitigation Mechanism:

The biological activity within the odor cells creates a micro-ecosystem that is actually a network of microorganisms interacting with a feedstock of emissions provided by the exhaust fans. These exhaust emissions actually supply nutrients to the microbes and they in turn break down the emissions thereby removing the undesirable characteristics. Microorganisms play a vital role in the normal biological cycles by converting organic compounds into elemental components (Shareefdeen, et al., 2005).

Creation and maintenance of a viable micro-ecosystem is a prominent feature of the odor cell technology. Enhancing conditions to promote maturity of the micro-ecosystem is a priority during the initial startup of the odor cells. The following principles are integral to the efficiency and performance of the odor cells:

1. Physical entrapment of particulates (Figure 3).
2. Timely and quantified hydration that stimulates and maintains microbial activity (Figure 4).
3. Rapid development and maintenance of a micro-ecosystem (Figure 5).

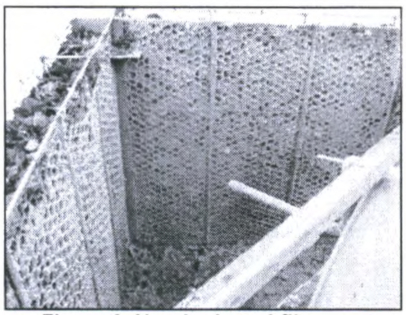

Figure 3. Non-hydrated filter after 4 months of operation.

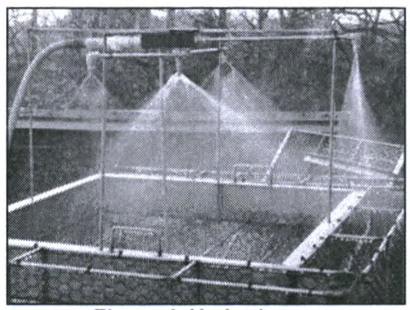

Figure 4. Hydration delivery system.

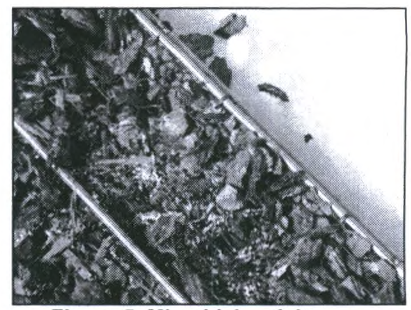

Figure 5. Microbial activity present during winter months.

The biological workhorses of this network are heterotrophic aerobic bacteria. They are a highly nutritionally diverse group of organisms which use a broad range of enzymes to chemically break down a variety of organic materials. Bacteria are single-celled and structured as rod-shaped bacilli, spherical-shaped cocci, or spiral-shaped spirilla. The characteristic earthy smell of soil is caused by actinomycetes, organisms that resemble fungi but actually are filamentous bacteria. In the filtering media, fungi break down tough debris such as cellulose allowing bacteria to continue the decomposition process. Fungi can breakdown organic residues that are too dry, acidic, or low in nitrogen for bacterial decomposition. Most fungi are classified as saprophytes because they live on dead or dying material and obtain energy by breaking down organic matter. Yeasts and molds (fungi) are present in acceptable levels to provide secondary support for breaking down organic compounds (BBC Laboratories, 2005). Each microorganism community interacts with unique and specific families of organic and inorganic substances surrounding it such as ammonia, hydrogen sulfide, and volatile organic compounds. The microbial community becomes more diverse and can accommodate an even wider range of emissions as it matures.

There are distinct phases within the growth of microorganisms (Figure 6). The log phase or exponential phase features rapid cell division and growth. The stationary phase marks conditions when viable count remains constant as the number of new cells counterbalances the number of dying cells. The log decline phase is characterized by a decrease in the viable population count. When the nutrient supply is a limiting factor, the microorganisms enter into the endogenous respiration phase. Reproductive growth is curtailed and some cells change to a dormant state (sporulation). Other organisms simply self-destruct. Total absence of a nutrient source will lead to massive cell death. OCT's selected media, pine bark, has a built-in "seed stock" of bacteria that can grow rapidly under the right conditions. Table 1 illustrates the growth of specific microbes within the pine bark at different time intervals.

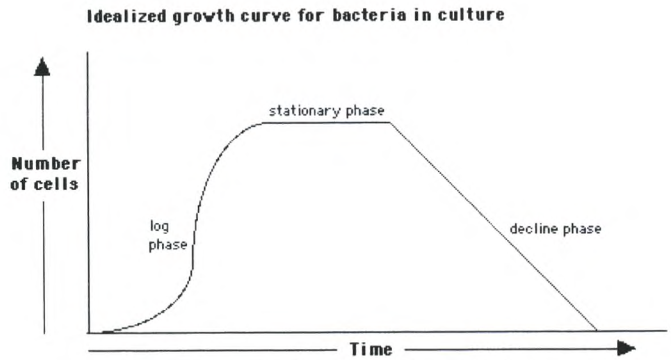

Figure 6. Growth of a microbial population.

Table 1. Growth of specific microbes at different time intervals.*

Duration	Organism	Level Found (cfu/g)**	Testing Method
Virgin Bark	Aerobic Plate Count	390,000 cfu/g	FDA III
	Mold	720 cfu/g	FDA XVIII
	Yeast	14,000 cfu/g	FDA XVIII
60 Day Bark	Aerobic Plate Count	1,100,000,000 cfu/g	FDA III
	Mold	770,000 cfu/g	FDA XVIII
	Yeast	Not Detected	FDA XVIII
180 Day Bark	Aerobic Plate Count	1,280,000,000 cfu/g	FDA III
	Mold	160,000 cfu/g	FDA XVIII
	Yeast	88,000 cfu/g	FDA XVIII

*Analysis conducted by Midwest Laboratories.
**Units are expressed in colony forming units per gram of substrate.

Heterotrophic bacteria are well within an adequate range of organisms necessary for a viable micro-ecosystem (100 million to 10 billion colony forming units per gram (cfu/g) (BBC Laboratories, 2005). As the aerobic micro-ecosystem matures, more species of microorganisms become active adding to the diversity of microorganisms available for breakdown of undesirable odors. Additionally, bacteria secrete distinctive enzymes that break down waste and toxins into simpler compounds that the bacteria can utilize as a food source. Enzymes respond to similar conditions that are present in a flourishing microbial population. Thus, environmental conditions that promote microbial growth and function mutually support active enzyme activity.

Consistency of the media is fundamental to the odor cell efficiency. Testing of the pine bark media yields a consistent porosity of 60%-62% (Nicolai, R. et al., 2001). The slowing of the air through the bark allows particle deposition within the media. The unique physical integrity of the pine bark allows particles to be entrapped in "micro-caverns" within the bark. Microbes can then breakdown these particulates over time. The microbes act as a "self-cleaning" mechanism for the odor cells. The porous layered structure of the bark results in much more surface area being exposed to exhaust emissions. Table 2 reports the effectiveness of the odor cell in reducing particulate emissions.

Table 2. Effectiveness of odor cells in reducing dust emissions.*

Duration**	Total dust inside	Concentration Inside	Total dust outside	Concentration Outside	% Reduction
24 hours	2.68 mg/filter	0.93 mg/m^3	0.10 mg/filter	0.035 mg/m^3	96.24%
48 hours	2.65 mg/filter	0.46 mg/m^3	0.34 mg/filter	0.059 mg/m^3	87.27%

*Analysis of samples conducted by Test America, Cedar Falls, Iowa
**Samples were collected December 18-20, 2007. Minimum ventilation fan (5700 cfm), 835 head present averaging 122.7 kg (270 pounds).

Optimal populations of microbes thrive in a 50% moisture content of the media. However, microbes can function in varying degrees in a 30%-65% range (Cundiff et al., 2003). An additional benefit of timely hydration is that the moisture can interact with gaseous emissions such as ammonia and hydrogen sulfide. This damp environment simulates a "scrubbing" action on these substances. Figure 7 illustrates typical ammonia reduction of the odor cells as the micro-ecosystem matures.

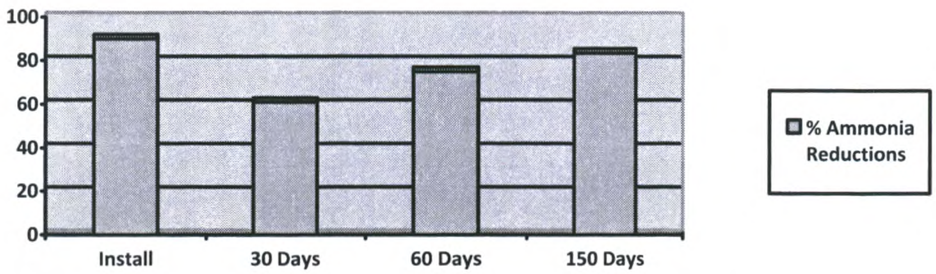

Figure 7. Ammonia reduction with maturation of the odor cell.

Applicability:

Odor cell technologies are effective at mitigating odor emissions in swine housing systems that employ direct-drive, pit exhaust fans in a range of 1500-10,000 cfm. Knowledge of the ventilation system's operational goals is essential in evaluating odor cell size and maximizing its capabilities. The considerations that need to be identified are:

- Identify minimum ventilation fan(s)
- Know the desired ventilation rate/pig space
- Establish the run-time requirements of each state of ventilation

Limitations:

Bio-filtration is most effective on organic compounds and particulate matter. It relies on a constant feedstock supply (air emissions) utilizing organic material as the filtering medium. Maintenance of the moisture level between 30% and 65% is critical to an active microbial population. The static pressure load on common fans is between .05 and .08 inches of water when pine bark is used. This load must be accounted for in calculating ventilation requirements, but allows implementation of the technology in most existing CAFO's without changing the ventilation system dramatically. Table 3 and Figures 8 and 9 illustrate the static pressure load on a 10-inch odor cell. The recommended media characteristics have been examined for several years. The selection of the media must meet three criteria: (1) consistent porosity (2) slow degradation rate, and (3) porous structural makeup. The recommended pine bark meets all three criteria. Substitution of media that do not meet all three criteria is not recommended.

Table 3. Typical static pressure load on a 10-inch odor cell.

Age of cell	Head pressure (inches of water)
30 days	0.050
90 days	0.044
150 days	0.061

Total pressure of the system (Vacuum + Head pressure) was .09 to .1 inches of water. The odor cell pressure on the ventilation fan was between .04 and .06 inches of water.

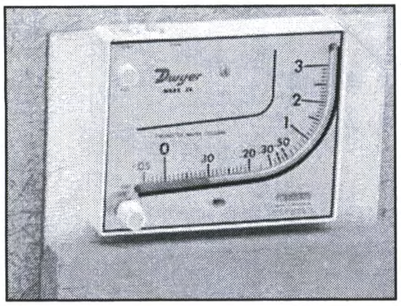

Figure 8. Dwyer manometer

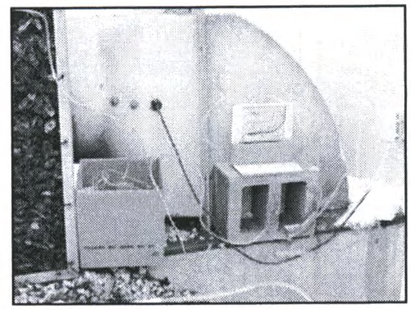

Figure 9. Head and vacuum testing

Cost:

Table 4 presents costs that would be expected using a 1200 head mechanically ventilated finishing unit with 6 pit fans:

Table 4. Estimated costs of a 1200 head finishing building.

Quantity	Description	Cost/unit	Total
6	Odor Cells (10 inch)		
	Internal/External Hydrators	$1650.00	$9900.00
6	Initial Bark Fills	$125.00	$750.00
6	Rock Base Pads	$20.00	$120.00
1	Hydrator Delivery Package includes:		
	60 feet ½ inch braided hose, 2 valves,		
	Timer, control box, 600 feet ¾ inch pvc pipe		$360.00
		Total	$11130.00
Shipping	$1.45/loaded mile (Spring 2008)	250 miles	$362.50
Optional items			
1	Rain Sensor	$55.00	($55.00)
1	Manometer	$50.00	($50.00)
6 Installations	Install and Fill Odor Cells	$50.00/cell	($300.00)

Assuming a 20-year life for a finishing building, this equates to $.48 per pig space for fixed costs. Assuming 2.6 turns per year over 20 years, the cost per pig produced would be $.18 for fixed costs. Operational and maintenance costs assuming a complete media change every 5 years would be $.14 per pig space and $.05 per pig produced. Labor is optional in this cost estimate. Odor Cell Technologies LLC usually demonstrates the proper installation of 1 odor cell at no charge. The implementation is quite straight forward and most site managers select to do the installation themselves. A turnkey installation quote can be supplied upon request. (Pricing is subject to input cost increases due to market volatility and fuel surcharges).

Implementation:

Once a producer has determined their ventilation requirements, he/she may elect to phase in technologies appropriate to odor mitigation goals and budget limitations. The more aggressive odor cells (10-inch) are generally placed on minimum ventilation fans with less aggressive cells implemented on subsequent stage fans based on run-time criteria. Other considerations include Iowa State University's air modeling, proximity to neighbors, predominant wind direction, proximity to public areas such as towns, parks, and nearby public roads. Additional federal, state, and local ordinances or site requirements such Minnesota's OFFSET (Jacobsen et al., 2002) need to be a part of the odor management plan. Figure 9 illustrates the different levels of technologies that may be used.

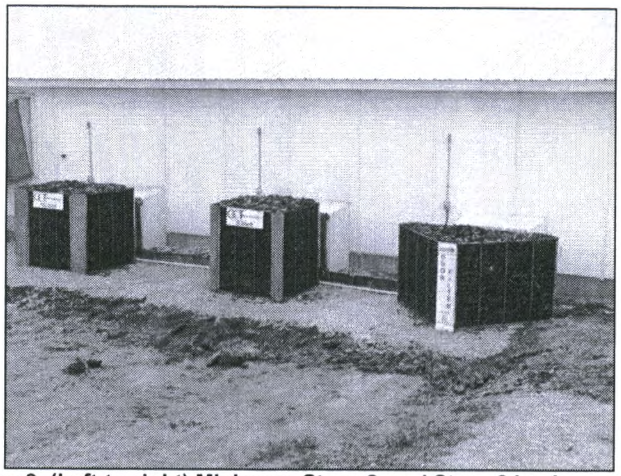

Figure 9. (Left-to-right) Minimum, Stage 2, and Stage 3 implementations.

The design of the odor cells allows visual inspection of the condition of the bark. At least 6 inches of media may be consumed before additional media is required. This can be easily observed through visual inspection of settling.

Normal maintenance usually includes the topping off of the cells in the spring and the fall. It is important to note that too much water affects microbial growth as well as too little. If too little moisture is present, microorganisms will sense that the environment is not conducive to growth and vitality and will go dormant. Too much water will result in accelerated decomposition of the bark and decrease the useful life of the media. The measurement of the moisture content of the media is easily monitored by visual inspection and physical handling of the media. Visual inspection includes observing dark “streaks” which are resident microbe colonies and probing the bark with one’s finger to feel dampness. Individual bark pieces can be evaluated by observing how the pieces respond to bending. If the bark “snaps” when broken (similar to a potato chip) it is on the low end of the moisture range and would require more watering. Ideally the bark will be pliable and flexible to bending. It is important to note that the media is to be “damp”, not wet. Most of the watering use will occur between the months of April through September/October. It is recommended that hydration cycles be repeated with greater frequency and less duration during these months. Large amounts of water are not required for hydration. The goal is to maintain 50% moisture content in the media. Most times this is a function of replacing the normal evaporation rates. Through the use of a timer, the hydrators can be programmed to maintain optimal conditions for the microorganisms to grow. Normal rainfall provides natural hydration and can substitute for normal hydration cycles. Rain sensors that override normal hydration cycles are very effective in preventing over-hydration. Since the odor cells are above ground, excess water does not build up within the media.

The main water nozzles on the hydrator are located on the outside of the odor cells and can be visually observed. In addition, an internal nozzle can be observed by lifting the center panel to check the spray pattern. Delivery of water to the filters is a site-specific choice of the facility owner. Options may include laying pvc pipe above ground, shallow trenching of irrigation tubing, dedicated internal/external lines, or ordinary garden hoses.

Technology Summary:

Odor Cell Technologies LLC has created a patented technology that significantly reduces odors commonly found in and around swine production facilities. Through the implementation of odor cells, odorous gases and particulate matter can be biologically broken down and reduced at the point source. Reducing the transfer distance of these odors improves air quality to the surrounding community. Peak efficiency of the odor cells is easily maintained by accessible monitoring of the conditions within the cell. Adaptability to ventilation requirements, flexibility in design, simplicity of installation, low maintenance and durability make this technology a sensible way to address odor issues. For approximately $.62 per pig space an effective odor mitigation strategy can be implemented that is environmentally friendly, aesthetically appealing and cost effective.

Acknowledgements:

Odor Cell Technologies LLC would like to recognize our best advocates - our customers. They are truly pioneers in air mitigation. Their feedback has been a valuable asset to our company. Many of their down-to-earth suggestions have been instrumental in refining our technologies.

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As published in the proceedings of:
MITIGATING AIR EMISSIONS FROM ANIMAL FEEDING OPERATIONS CONFERENCE
Iowa State University Extension
Iowa State University College of Agriculture and Life Sciences
Conference Proceedings
Sponsored by:
NRI Air Quality Extension & Education
Iowa Farm Bureau Federation
Iowa Egg Council
Iowa Pork Industry Center
Iowa Pork Producers Association
U.S. Pork Center of Excellence

Multi-pollutant Scrubbers for Removal of Ammonia, Odor, and Particulate Matter from Animal House Exhaust Air

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Animal Sciences Group, Wageningen University and Research centre, The Netherlands

Species: Swine and Poultry
Use Area: Animal Housing
Technology Category: Scrubber
Air Mitigated Pollutants: Ammonia, Odor, Particulate Matter (PM10, PM2.5)

Description:

Intensive poultry and pig operations concentrated in the south and east of the Netherlands are major contributors to ammonia, odor and particulate matter (PM) emissions. In the Netherlands, livestock production is responsible for 95% of the national ammonia emission causing acidification and eutrophication of natural ecosystems, and 50% of the total emission of all acidifying compounds (Koch *et al.*, 2003; EDC, 2007). Furthermore, odor emissions from animal housing and land application of manure are being increasingly considered a nuisance in densely populated countries as the scale of livestock operations expands and an increasing number of rural residential developments are built in traditional farming areas. Finally, a large number of premature deaths and health problems are associated with the emission of particulate matter (PM) (Mokdad *et al.*, 2004; WHO, 2006b), *i.e.* tiny solid or liquid particles that are suspended in the air (e.g. dust, dirt, soot, smoke, and liquid droplets). Approximately 20% of the primary PM10 production in the Netherlands is estimated to originate from poultry and pig operations (Chardon and Hoek, 2002)[1]. Besides, ammonia is a known precursor of secondary particulates so by being a significant emitter of ammonia, livestock farming also contributes indirectly to PM emissions. New air quality regulations from the World Health Organization (WHO) and European Union (EU) impose limits on PM10 and PM2.5 emissions on al major sources, including farms, to keep PM concentration in ambient air below critical standards to protect human health (EC, 1999, 2005; WHO, 2006a).
In several European countries (Germany, Denmark, Netherlands), one-stage acid scrubbers and bio-scrubbers are considered off-the-shelf techniques for effective removal of ammonia from exhaust air from pig houses and, to less extent, for poultry houses and odor removal (Melse and Ogink, 2005). In Table 1 the market size of air scrubbers is shown for livestock operations in the Netherlands as per January 1st 2008.

Table 1. Scrubber application for ammonia removal in pig and poultry operations in the Netherlands (based on statements from manufacturers, as per January 1st, 2008).

	Installed capacity (m3/hour)	**Number of farms**
Acid scrubbers	64 million	790
Biotrickling filters	14 million	90
Total:	79 million	880
Pig	76 million (*)	850
Poultry	3 million (**)	30
Total:	79 million	880

(*) This equals 10% of the exhaust air of all pig farms nationwide.
(**) This equals 0.4% of all exhaust air of all poultry farms nationwide.

Currently, a new generation of scrubbers is being developed for livestock operations: "multi-pollutant air scrubbers". This type of scrubber should be able to drastically reduce the emission of not only ammonia but of three pollutants:

- Ammonia
- Odor
- Particulate matter (PM10 and PM2.5).

Multi-pollutant air scrubbers usually consist of two or more scrubbing stages, each stage aims for the removal of one type of compounds. The first prototypes of multi-pollutant scrubbers for pig farms, combining the concepts of acid scrubbing, bio-scrubbing, water-curtains, and biofiltration have recently been tested in Germany (Arends *et al.*, 2006)

[1] PM10 (also called inhalable particles) represents the fraction of particles that have an aerodynamic diameter of 10 µm or less; PM2.5 (also called respirable particles) is used to describe the particles fraction with an aerodynamic diameter of 2.5 µm or less. The aerodynamic diameter is the diameter of a spherical particle having a density of 1 kg/m3 that has the same terminal settling velocity in the gas as the particle of interest.

and the Netherlands, and are in operation now at a limited number of farms. Recent research on particulate matter removal by such multi-pollutant air scrubbers showed an average removal efficiency ranging from 62 to 93% for PM10 and from 47 to 90% for PM2.5 (Aarnink *et al.*, 2007, 2008a, 2008b; Ogink and Hahne, 2007). These data suggest that end-of-pipe air treatment may be of major importance for compliance with current and future PM10 and PM 2.5 standards. Data on PM removal by one-stage ammonia scrubbers (acid scrubbers or biological air scrubbers) is currently not available.

Market conditions demand an increasing scale of operation for both pig and poultry farms whereas air quality regulations restrict their size, unless emissions can be drastically reduced. Multi-pollutant scrubbers may play an important role here. It is expected that within the next years the implementation of air scrubbers will expand in intensive livestock production areas in Europe to comply with European regulations for the protection of natural ecosystems and ambient air quality. However, considerable research and development efforts are needed to keep operational costs at acceptable levels.

Recently, an innovation and implementation program has been set up by the Dutch national government that aims to stimulate the development and introduction of multi-pollutant air scrubbers. The program includes farm-scale research on five pilot locations where experimental multi-pollutant scrubbers are tested during a three-year period.

The objectives of this paper are to:

- Give an overview of technical principles applied in scrubbers for livestock operations.
- Present the preliminary results of the Dutch research program on multi-pollutant scrubbers with regard to removal efficiencies and operational parameters of these scrubbers.

Mitigation Mechanism and Applicability:

Acid scrubbers and bio-scrubbers

Since the 1990's, single-stage air scrubbers have been implemented on intensive livestock operations mainly to minimize ammonia emissions for the protection of nearby located sensitive ecosystems. Two types of scrubbers have been generally applied: 1) acid scrubbers, 2) bio-scrubbers or biotrickling filters.

Acid scrubbers are based on the entrapment of ammonia in acid liquid that is recirculated over a packed bed and the frequent discharge of the resulting ammonium salt solution at a concentration of about 150 g/L. Usually sulfuric acid is applied and pH is kept between 2 and pH 4. Melse and Ogink (2005) reported average ammonia removal efficiencies of 96% for farm-scale operated acid scrubbers. Reported average removal efficiency for odor was only 31% and showed a large variation. Acid scrubbers are considered as a state-of-the-art technique in cases where very high reductions of ammonia emissions are required.

In bio-scrubbers, or biotrickling filters, bacteria convert ammonia into nitrite and nitrate. Nitrogen concentrations in the water are kept below inhibiting levels by regular discharge of the recirculation liquid. The biomass is partly attached to the packed bed and partly suspended in the recirculation liquid. As compared to chemical scrubbers the discharge volume of biotrickling filters is about 8 to 10 times higher. Average ammonia removal efficiency at farm operations amounted 70%, whereas for odor removal a large variation was found with an average removal efficiency of 44%. In general, biotrickling filters have a higher odor removal potential than acid scrubbers because a wide array of odor components dissolved in the circulation water are broken down by the biomass, whereas in chemical scrubbers only part of the odor components are kept in solution due to a low pH.

Scrubbers are mainly applied in pig housings with central ventilation ducts. Only a few examples are known where they are applied in poultry houses. The high dust content of ventilation air increases the risks of blockage of the packing bed causing high pressure drop and increased energy use.

Multi-pollutant scrubbers

In the late 1990's, multi-pollutant air scrubbers for livestock operations were initially developed in Germany to ensure a high and sustainable removal of livestock odor (Arends *et al.*, 2006; Hartung *et al.*, 2006). The basis of this development was the known high odor removal capacity of biofilters with an organic packing material (usually a mixture of materials like compost, wood bark, wood chips, peat, perlite, and organic fibers), which is related to the huge absorption capacity per unit of volume. The functioning and lifespan of the biofilter is improved by pre-treating incoming air, leading it first through an acid scrubber and mist eliminator before entering the biofilter. This approach addresses four general disadvantages associated with the use of biofilters with organic packing material in livestock operations:

- By removing the main part of the ammonia load before entering the biofilter the formation of nitrite/nitrate salts is minimized. High ammonia loads eventually result in excessive nitrite/nitrate concentrations that block a proper functioning of micro-organisms in the biobed and leads to acidification, thus undermining the removal capacity of the bed, often without being noticed by users. In practice this can be prevented by replacement of the biofilter packing at regular intervals. Pre-treating the air allows a much longer packing lifetime, and thus reduces refilling costs.

- Biofilters have to be kept moist for adequate microbial functioning. Especially at the air inlet side the filterbed may dry out because the inlet air is not water saturated. By scrubbing the incoming air first, the air will be water saturated and helps to moisten the filter bed.
- Biofilters are sensitive to dust loads that clog the packing, increase the pressure drop, and subsequently lead to increase of ventilation energy. Together with inadequate moistening, clogging may lead to preferential air flows which will decrease the removal performance of the filter bed. By scrubbing the air first, total dust load is drastically reduced.
- The total pressure drop over the filterbed can be very high in practice (>200-300 Pa) and requires a relatively high energy input per unit of air volume. By pre-treating the air by a scrubber the height of the filter bed can be reduced thus reducing the pressure drop.

In a subsequent development the concept of specialized treatment for different compounds in consecutive scrubbing units has been further improved. Instead of one pre-treating scrubbing step, two scrubbing steps are implemented followed by a vertically oriented biobed. The first step consists of packing material over which water is recirculated to remove dust, the second step operates as an acid scrubber to remove ammonia, and the third step is designed as a biobed wall to remove the remaining odor. The collection basins are separated, and a mist eliminator is placed between the acid step and biobed. By placing the treatment steps as three consecutive walls on short distance directly after each other, the air can pass straightforward through the system without extra turns that increase the pressure drop. A few Dutch and German companies produce installations for pig farms based on this three-step approach. Further modifications involve two-phase setups leaving out the biobed, where an acid-based treatment for ammonia removal is followed by a water-based treatment to remove remaining odors, and where discharge water of the water treatment is used as recirculation liquid in the first acid-based phase. Eventually, a water-based treatment step might turn into a biotrickling step. Recently, manufacturers have started to develop and test denitrification treatment in order to reduce the amount of water that might be discharged from the biotrickling stage.

Running Research Program on Multi-pollutant Scrubbers:

Description of pilot program

In 2007, a three-year research program, funded by the Netherlands Ministry of Housing, Spatial Planning and the Environment (VROM), started that aims to promote successful application of multi-pollutant scrubbers at livestock operations. The goal of the program is to gain knowledge that will help scrubber manufacturers with the development of a new generation of scrubbers that not only remove ammonia but also achieve high removal efficiencies (at least 70%) for odor and particulate matter (PM10 and PM2.5). During a period of three years the operational parameters and removal efficiencies of ammonia, odor and particulate matter are followed on five farm locations where multi-pollutant scrubbers have been installed by four Dutch manufacturers. Based on these long-term experiences modifications and improvements will be proposed and realized. In Table 2 some characteristics of the pilot-locations are summarized. Empty bed residence times at maximum ventilation rates are between 0.1 and 1.6 s.

Table 2. Description of experimental multi-pollutant scrubbers at pilot locations in the Netherlands which are included in research program.

Pilot location	Animal category	Installed ventilation capacity (m^3/hour)	EBRT (s)	Description [a]
1	30,000 broilers	75,000 [b]	8.9	Biotrickling filter (cross-flow) + denitrification unit
2	182 farrowing sows + 2,640 piglets	81,000	6.5	Acid scrubber + water scrubber (cross-flow)
3	400 dry and pregnant sows	60,000	16.6	Acid scrubber + water scrubber (cross-flow)
4	2,600 fattening pigs	160,000	72	Biotrickling filter (counter-current flow) + denitrification unit
5	21,000 broilers	180,000	6.2	Acid scrubber + water scrubber(counter-current flow)

[a] EBRT = Empty Bed Residence Time (s), calculated as the volume of packing material (m^3) divided by the air flow rate (m^3/s).
[a] A water scrubbers can be considered as a biotrickling filter on the long term as usually biomass develops.
[b] The inlet air is treated in a heat exchanger connected to groundwater which results in lower ventilation rates.

Methods

General

The ammonia, odor and particulate matter measurements are carried out according to three protocols that are being developed by us on request by the Dutch government; the protocols will become mandatory in the near future.

Ammonia measurements

The NH_3 concentration in the inlet and outlet of the scrubber system is measured using an impinger ("bubble flask") method. A fraction of the air to be sampled is continuously drawn at a fixed flow rate which is controlled by a critical orifice (usually 1 L min^{-1}) through a pair of impingers (0.5 L each) containing an strong acid solution (usually nitric acid, 0.03 - 0.2 M), connected in series (Van Ouwerkerk, 1993). NH_3 is trapped by the acid and accumulates in the bottles; after 24 hours the measurement is stopped and the bottles are disconnected. Fluctuations in the NH_3 concentration of the sampled air are thus time-averaged over 24 hours. The values of the sampling flow rate and nitric acid concentration are chosen so that the second impinger, which serves as a control, does not contain more than 5% of the amount of NH_3 trapped in the first impinger. All sampling tubes have been made of Teflon, are isolated, and heated with a coil of resistance heating wire to a temperature that is approximately 20°C higher than the ambient temperature to prevent condensation of water and subsequent adsorption of NH_3. Finally, the NH_3 concentration of the air is calculated from the nitrogen content of the acid solution in the bottles, which is determined spectrophotometrically (NNI, 1998a), and the given air sampling flow rate.
The ammonia removal efficiency is expressed as ([NH_3-in] - [NH_3-out]) / ([NH_3-in]) x 100%.

Odor measurements

For odor measurement, an air sample is collected in an initially evacuated Teflon odor bag (60 L). The bag is placed in an airtight container, the inlet of the bag is connected to the sampling port of the air inlet or air outlet of the scrubber and the bag is filled by creating an underpressure in the surrounding airtight container by means of a pump. The air sampling flow rate is controlled by a critical orifice (0.5 L min^{-1}) and the odor bag is thus filled in two hours time, from 10:00 AM to 12:00 AM. In this way fluctuations in the composition of the air sample are time-averaged over two hours. A filter (pore diameter: 1 - 2 μm) at the inlet of the sampling tube prevents the intake of dust that otherwise will contaminate the olfactometer. The sampling system is equipped with a heating system to prevent condensation in the bag or in the tubing. An odor bag remains in the container until analysis in the odor laboratory, which has to take place within 30 hours after sample collection. Odor concentrations are determined in compliance with the European olfactometric standard EN13725 (CEN, 2003) and the preceding Dutch olfactometric standard NVN2820/1A (NNI, 1996) that has been incorporated in the European standard. In both standards, the sensitivity of the odor panel is based on the 20 - 80 ppb n-butanol range. The odor concentrations are expressed in European Odor Units per m3 air (OUE m^{-3}) (CEN, 2003). The accuracy of the sensory-based odor measurements is lower than the accuracy of common analytical measurements. From an analysis on the accuracy of odor measurements, using olfactometric standards that comply with the EN13725 standard (Ogink *et al.*, 1995), standard errors can be calculated for single odor measurements under repeatability conditions that range between 15 and 20%.
The odor removal efficiency is expressed as ([Odor-in] - [Odor-out]) / ([Odor-in]) x 100%.

Particulate matter (PM) measurements

The dust concentrations (PM10 and PM2.5) of the incoming and outgoing air of the scrubbers were sampled for 24 hours. PM10 and PM2.5 were simultaneously measured. Dust concentrations were measured by drawing a known amount of air at a fixed air speed through a sampling head. Cyclone pre-separators for PM10 and PM2.5 within the sampling head separated the larger dust particles from the fractions that had to be measured (PM10 or PM 2.5) as described by Aarnink *et al.* (2008). PM10 and PM2.5 samples were collected on a glass fiber filter. The filters were weighed before and after sampling under standard conditions (NNI, 1998b; NNI, 2005).
The PM removal efficiency is expressed as ([PM-in] - [PM-out]) / ([PM-in]) x 100%.

Preliminary results

In Table 3 the first results of the ammonia, odor and particulate matter removal efficiency measurements are shown for the different multi-pollutant scrubbers. All measurements were carried out during normal scrubber operation; when it was clear that a scrubber system was malfunctioning or had been malfunctioning recently (*e.g.* the system had ran out of acid, control parameters of the system were out of normal ranges, fresh water supply was halted) measurements were postponed for a week.

Table 3. Preliminary results of the measured removal efficiencies for ammonia, odor, and particulate matter (PM) by the farm-scale multi-pollutant scrubbers.

Ammonia removal	Odor removal	PM10 removal	PM2.5 removal
63 - 98% average: 83% n = 7	0 - 83% [a] average: 40% n = 8	41 - 46% average: 43% n = 2	23 - 61% average: 42% n = 2

[a] Actually, in two cases an increase of the odor concentration was found.

Table 3 shows that the aimed ammonia removal of at least 70% can usually be achieved. The odor and PM removal, however, is much lower and needs to be increased in order to meet the requirement of 70% removal. It must be noted that the number of PM measurements is low at present. An analysis of known PM removal efficiencies by scrubbers reveals that the removal efficiency is probably proportional to the air residence time in the packing (Aarnink *et al.*, 2007, 2008a, 2008b).

Future measurements will be carried out in the coming two years in order to get reliable data on long-term performance of the multi-pollutant scrubber systems. Based on the results additional research will be carried out in order to improve performance, reliability, and stable operation of the systems. Although the multi-pollutant scrubbers are running at farm-scale size, they are still being considered as experimental systems at present.

Cost:

In Table 4 a cost-calculation is given both for acid scrubbers, biotrickling filters and multi-pollutant scrubbers, based on a newly built production facility. In case of modification of a pig house, investment costs will be higher because the ventilation system has to be modified from (usually) separately ventilated compartments to a central ventilation duct. Multi-pollutants scrubbers require a higher investment as compared to the other scrubber systems. These extra costs are related to the extra scrubbing phases that are included. Investments in extra ventilation capacity are the same for both scrubber types. It is expected that with the introduction of more multi-pollutant scrubber systems and larger series volumes, investment differences between conventional and multi-pollutant scrubbers will get smaller.

The total operational costs of multi-pollutant scrubbers are expected to be about 5% lower than for biotrickling filters. This is due to the reuse of discharge water from the biotrickling step in the acid scrubbing step, thus reducing the amount of discharge water and partly replacing the fresh water intake. As compared to acid scrubbers, the total operational costs of multi-pollutant are expected to be about 25% higher, mainly due to fixed costs of the investment.

Table 4. Investment and operational cost of scrubbers for newly built production facilities in € / animal space (based on Arends *et al.*, 2006; Melse and Ogink, 2005; Melse and Willers, 2004; Ogink and Bosma, 2007) [a].

	Acid scrubber	Biotrickling filter	Multi-pollutant scrubber (3-stage water/acid/biotrickling)
Investment costs	32.8	43.5	50.3
Operational costs (year^{-1})			
Depreciation (10%)	2.6	3.4	4.2
Maintenance (3%)	1.5	1.8	2.0
Interest (6%)	0.8	1.0	1.2
Electricity use (€ 0.11 kWh^{-1})	3.3	3.8	3.7
Water use (€ 1.0 m^{-3})	0.6	1.7	0.6
Chemical use (€ 0.6 L^{-1} H_2SO_4, 98%)	1.4	n/a [c]	0.7
Water discharge [b]	0.6	2.5	1.0
Total operational costs (year^{-1})	10.8	14.3	13.5

[a] The investment costs are based on a maximum ventilation capacity of 60 m^3 animal place^{-1} h^{-1}.
[b] Water disposal costs are assumed of € 10/m^3 for discharge from acid scrubbing and € 2/m^3 for discharge from biotrickling or water scrubbing. For the multi-pollutant scrubber, discharge water from the biotrickling or water scrubbing step is reused in the acid scrubbing step. The systems do not include a denitrification unit which might significantly decrease water discharge costs.
[c] n/a = not applicable.

Important aspects for possible cost reduction are reduction of energy and alternative use or treatment of discharge water (*e.g.* denitrification, optimization of discharge control). Furthermore, decreasing scrubber size, which can *e.g.* be made possible by using bypass options at maximum ventilation (Melse *et al.*, 2006) or by cooling of incoming ventilation air, will reduce costs.

Technology Summary:

In The Netherlands, Germany and Denmark packed-bed biotrickling filters and acid scrubbers for removal of ammonia from exhaust air of animal houses are off-the-shelf techniques. These scrubbers are mainly applied in pig housings with central ventilation ducts; only a few are applied in poultry housings because of the relatively high dust concentrations in this air. At the moment a new generation of so-called "multi-pollutant scrubbers" is being developed and tested that not only remove ammonia but also aim for significant removal (at least 70%) of odor and particulate matter (PM10 and PM2.5) from the air. This combination provides an attractive option for large scale livestock operations to remain in operation in areas with nearby located residential areas and sensitive ecosystems. Multi-pollutant air scrubbers usually consist of two or more scrubbing stages where each stage aims for the removal of one type of compounds. Recently a 3-year research program has started that monitors and aims to improve the performance of five farm-scale multi-pollutant scrubber from different manufacturers. The preliminary results show that ammonia removal is relatively high but that the removal of odor and particulate matter needs to be improved further. Finally a detailed cost calculation is presented.

Acknowledgments:

The financial support to carry out this work by the Netherlands Ministry of Housing, Spatial Planning and the Environment (VROM) and by the Netherlands Ministry of Agriculture, Nature Management and Food Quality (LNV) is gratefully acknowledged.

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As published in the proceedings of:
MITIGATING AIR EMISSIONS FROM ANIMAL FEEDING OPERATIONS CONFERENCE
Iowa State University Extension
Iowa State University College of Agriculture and Life Sciences
Conference Proceedings
Sponsored by:
NRI Air Quality Extension & Education
Iowa Farm Bureau Federation
Iowa Egg Council
Iowa Pork Industry Center
Iowa Pork Producers Association
U.S. Pork Center of Excellence

Mitigation of Odor and Pathogens from CAFOs with UV/TIO$_2$: Exploring Cost Effectiveness

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Species: Swine, Poultry
Use Area: Animal Housing
Technology Category: UV photocatalysis
Air Pollutants Mitigated: Volatile Organic Carbon, odor, and pathogens

Description:

Livestock operations are sources of aerial emissions of odor, volatile organic compounds (VOCs), ammonia, hydrogen sulfide, and bioaerosols, including pathogens (National Research Council, 2003). At the same time these operations are potentially threatened with infectious diseases impacting national economies and food supply security. Comprehensive solutions to these multidisciplinary problems are needed. Our long-term objective is to develop and apply a novel treatment technology that would minimize the environmental impact of swine operations and at the same time would protect them and the public from the spread of infectious diseases.

This paper reports feasibility tests of lab-scale treatment of aerial emissions of selected VOCs responsible for livestock odor and inactivation of airborne pathogens by low-wattage UV light. The long-term goal is to develop cost-effective technology for the simultaneous treatment of odor and pathogens in livestock housing through logical progression of testing from lab-scale, through pilot-scale and finally at commercial scale. Such treatment would be applicable to both the inflow (for airborne pathogen control) and outflow air (for odor and pathogen control) at typical existing and new mechanically-ventilated barns.

Several target VOCs responsible for livestock odors were selected for testing effectiveness of UV light on odor. The selection of key odorants for lab-scale tests was based on previous work (Wright et al., 2005; Koziel et al., 2006, Bulliner et al., 2006). These include p-cresol, sulfur-containing VOCs, and volatile fatty acids. The effects of UV treatment time on the effectiveness of gas and odor removal were tested. The treatment times, gas flow rates, and UV energy used were then extrapolated to estimate theoretical cost of UV treatment of odor for typical ventilation rates and electricity cost at a swine finish operation in Iowa.

Mitigation Mechanism:

Odor and target VOCs responsible for livestock odor are mitigated by UV-185 nm ('deep' UV) in presence of TiO_2 as a catalyst into less odorous or odorless products such as CO_2 and H_2O. The chemistry behind can be shown as follows:

$$TiO_2 \xrightarrow{h\nu} e^- + h^+$$
$$h^+ + H_2O \rightarrow OH\bullet + H^+ \text{ (in presence of water vapor)}$$
$$e^- + O_2 \rightarrow O_2^-\bullet$$
$$O_2^-\bullet + H^+ \rightarrow HO_2\bullet$$
$$\text{VOCs/Odorants} + \textit{oxidants} \rightarrow \text{(less odorous) partially oxidized species} + CO_2 + H_2O$$

The effectiveness of UV light in treating VOCs and pathogens is well known in water treatment applications. Relatively little is known about gas-phase chemistry of odorous VOCs and inactivation of airborne pathogens with UV (Yang et al., 2007). Several advantages exist for gas-phase UV treatment compared to aqueous phase. These include: (1) lower levels of UV energy are needed compared with liquid phase; (2) degradation rates in air are typically higher; (3) gas-phase reactions allow the application of analytical tools enabling to monitor reaction rates and elucidate mechanisms; (4) the diffusion of reagents and products is much faster compared with liquid phase; (5) HO•

scavengers present in water do not interfere; (6) electron scavengers such as oxygen are rarely limiting; and (7) the lower absorption of photons by air compared with water.

With the addition of TiO_2 photocatalyst beds, additional oxidative processes occur at the gas-solid interface, through entirely different mechanisms that offer additional pathways to degrade recalcitrant VOCs. By nature, the catalyst beds are self-cleaning under exposure to UV light and air and add additional efficiency to the oxidative system. Titanium dioxide-mediated photocatalysis have also been shown to be effective at inactivation of pathogens.

Applicability:

The long-term goal is to develop cost-effective technology for the simultaneous treatment of odor and pathogens in livestock and poultry barns with mechanical ventilation. Such treatment would be applicable to both the inflow and outflow air. The inflow air could be treated with UV light for pathogens in the times of highly infectious diseases during which an isolation and protection of farm animals might be needed. Treatment of exhaust air with UV light would be used for odor and pathogens. Commercial scale systems would be applicable to new barns as well as to retrofit existing barns.

In this research, we measured the effectiveness of odor treatment and pathogen inactivation in laboratory scale. Summary of chemical percent reduction for target gases (selected odor-causing VOCs and H_2S) and % reduction of odor caused by each target gas is presented in Tables 1 and 2. Almost 100% removal was achieved for all the compounds tested except H_2S and dimethylsulfide using only 1 sec irradiation. Longer UV irradiation times resulted in improved percent reduction of target compounds and odor. Of specific interest is the removal of *p*-cresol which has been recognized as priority odorant responsible for the characteristic livestock odor (Wright et al., 2005; Koziel et al., 2006; Bulliner et al., 2006).

Table 1 – Chemical reduction% of target gases with different UV exposure times and TiO_2 catalyst

	% Reduction = (Control-Treatment)/Control*100%							
UV exposure (sec)	1	3	5	7	10	30	60	300
H_2S	10.2	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Methylmercaptan	80.0	81.4	96.3	87.1	57.9	100.0	100.0	100.0
Ethylmercaptan	94.7	96.5	100.0	96.9	59.2	100.0	100.0	100.0
Dimethylsulfide	48.2	18.6	47.3	85.5	70.4	99.8	100.0	100.0
Butylmercaptan	94.3	100.0	100.0	100.0	78.3	90.4	100.0	100.0
Acetic acid	99.4	99.5	99.1	99.4	97.1	97.1	98.9	100.0
Propanoic acid	99.9	99.9	99.9	100.0	99.7	99.8	99.6	100.0
Butyric acid	99.9	99.8	99.9	99.9	99.7	100.0	99.5	100.0
Isovaleric acid	99.6	99.3	99.3	99.5	99.7	99.8	98.9	99.9
P-cresol	99.5	99.2	99.4	97.2	97.5	99.3	98.0	99.9

Table 2 - Odor reduction% of target gases with different UV exposure time and 25 mg TiO_2 catalyst

	Reduction% = (Control-Treatment)/Control*100%							
UV exposure (sec)	1	3	5	7	10	30	60	300
H_2S	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Methylmercaptan	38.0	52.0	60.0	62.0	38.0	100.0	100.0	100.0
Ethylmercaptan	51.0	58.8	100.0	100.0	31.4	100.0	100.0	100.0
Dimethylsulfide	42.9	64.3	68.6	71.4	47.1	70.0	100.0	100.0
Butylmercaptan	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Acetic acid	85.4	92.7	100.0	100.0	100.0	100.0	72.0	100.0
Propanoic acid	82.1	100.0	100.0	100.0	64.3	100.0	100.0	100.0
Butyric acid	81.8	87.0	100.0	100.0	100.0	100.0	100.0	100.0
Isovaleric acid	73.5	73.5	78.3	80.7	100.0	100.0	100.0	100.0
P-cresol	89.0	90.2	91.5	82.9	85.4	85.4	100.0	100.0

Limitations:

Our team is still working on addressing some of the potential limitations of UV treatment. These include (a) testing the shortest possible treatment times that are consistent with fast air flow in a mechanically ventilated barn, (b) the presence of particulate matter (PM), and (c) production of reactive ozone gas during UV irradiation.

Cost:

Electricity cost for UV treatment is summarized in Table 3. This cost was estimated assuming that certain variables in laboratory scale such as the treatment time, UV lamp wattage, treated airflow rate, respectively, can be used to extrapolate the cost of electricity in full scale swine finisher barn (Table 4). It was assumed that the same lamp is treating full-scale ventilation airflow rate at the rural electricity cost. Table 3 summarizes the cost of electricity for 3 growing cycles on a real swine operation in central Iowa and the cost of UV as fraction of the total electricity cost. Cost of electricity associated with UV treatment is also presented on the basic of continuous operation as well as the intermittent operation for 12, 8, and 1 hr, respectively.

Table 3. Estimated electricity cost associated with UV treatment per pig during three growing cycles

	Cycle1 (01/30/04~06/18/04)	Cycle2 (06/25/04~11/24/04)	Cycle3 (12/16/04~04/24/05)
Season	Transitional	Warm	Cool
Mean air flow (m^3/s)	723.8	1124.6	546.6
Total air flow per cycle (m^3)	6.25E+07	9.72E+07	4.72E+07
Average # of pigs sold	828	810	950
UV electricity cost ($)	191.9	298.2	144.9
Based on UV lamp operating for 24 hrs per day			
UV electricity cost/pig sold ($)	0.23	0.37	0.15
UV treatment/ total electricity (%)	8.50	13.49	5.59
Based on UV lamp operating for 12 hrs per day			
UV electricity cost/pig sold ($)	0.116	0.184	0.076
UV treatment/ total electricity (%)	4.25	6.74	2.79
Based on UV lamp operating for 8 hrs per day			
UV electricity cost/pig sold ($)	0.077	0.123	0.051
UV treatment/ total electricity (%)	2.83	4.50	1.86
Based on UV lamp operating for 1 hr per day			
UV electricity cost/pig sold ($)	0.010	0.015	0.006
UV treatment/ total electricity (%)	0.35	0.56	0.23

Table 4. Assumptions used for extrapolation of electricity cost in Table 3.

cost of KWh ($)	0.087	Electricity per UV reactor (KWh)	7.06E-09
light intensity (mW/cm^2)	0.25	Electricity cost per UV reactor ($)	6.14E-10
reactor surface area (cm^2)	101.6	Volume of UV reactor (mL)	200
treatment time (sec)	1	cost of total UV treatment ($\$/m^3$)	3.07E-06

For a continuously operating system, the estimated average electricity cost of UV treatment per pig sold was $0.23, $0.37, and $0.15, for transitional, warm and cool seasons, respectively. The cost can be further reduced by intermittently operating the treatment system on as needed basis. For example, if UV lamp was to be operated for 1hr per day, the cost would be lowered to $0.006 and $0.015 (Table 3). The fraction of electricity cost for UV treatment would be only 0.23 to 0.56%.

Implementation:

To date, the UV treatment for odor mitigation and pathogen inactivation is still at laboratory scale. The illustration of full scale application to exhaust air is shown in Figure 1. Additional extension of the exhaust fan nozzle could be installed to divert the effluent upwards. This additional chimney-like channel could be used to (a) mount UV lamp(s) and (b) to improve dispersion of exhaust air. It is also an advantage that the UV lamps are activated by simple on/off switch. Theoretically, each fan could be retrofitted with such add-on system.

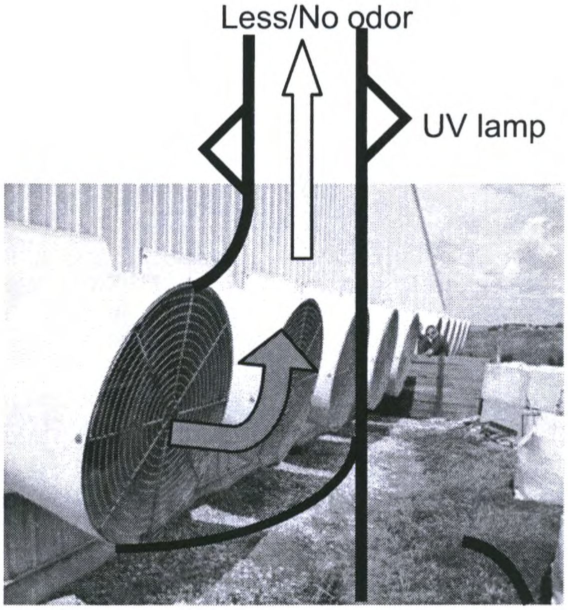

Figure 1. Schematic of scaled up UV treatment of exhaust air for odor and inactivation of airborne pathogens.

Technology Summary:

Odor and target VOCs responsible for livestock odor are mitigated by UV-185 nm ('deep' UV) in presence of TiO_2 as a catalyst into less odorous or odorless products such as CO_2 and H_2O. Percent removals from 80 to 99% were measured in lab-scale experiments involving simulated livestock VOCs/odorants and 1 sec irradiation with a low wattage 5.5 W lamp. Selected VOCs simulating livestock odor included p-cresol, sulfur-containing VOCs, and volatile fatty acids. Treatment cost of $0.25 per pig and continuous operation during growing cycle was estimated when the lab-scale results were extrapolated to typical ventilation rates and electricity cost at a swine finish operation in rural Iowa. The long-term goal is to develop cost-effective technology for the simultaneous treatment of odor and pathogens in livestock housing through logical progression of testing from lab-scale, through pilot-scale and finally at commercial scale. Such treatment would be applicable to both the inflow (for airborne pathogen control) and outflow air (for odor and pathogen control) at typical existing and new mechanically-ventilated barns.

Additional Resources:

http://www.abe.iastate.edu/odor

Acknowledgments:

The authors gratefully acknowledge the financial support provided by National Pork Board and Binational Agricultural Research and Development Fund.

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As published in the proceedings of:
MITIGATING AIR EMISSIONS FROM ANIMAL FEEDING OPERATIONS CONFERENCE
Iowa State University Extension
Iowa State University College of Agriculture and Life Sciences
Conference Proceedings
Sponsored by:
NRI Air Quality Extension & Education
Iowa Farm Bureau Federation
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Iowa Pork Industry Center
Iowa Pork Producers Association
U.S. Pork Center of Excellence

Waste Storage-Amendments and Covers

Effects of Sodium Bisulfate on Alcohol, Amine, and Ammonia Emissions from Dairy Slurry

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L. Nuckles, I. Malkina, and V. Arteaga
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Species: Dairy Cows
Use Area: Animal Housing
Technology Category: Chemical Amendment
Air Mitigated Pollutants: Ammonia, Amines, Alcohols

Description:

While research efforts in the past have focused on control technologies that deal with liquid dairy waste storage and treatment, ongoing research identified fresh slurry in the animal housing areas to be a major source of volatile organic compounds (VOC) and ammonia. Therefore, management practices have to be implemented to effectively address emissions from fresh slurry (Dragosits et al., 2002).

Alcohols are produced during anaerobic fermentation in the cow's rumen by microbial strains like *Streptococcus bovis* and *Ruminococcus albus*. Fresh slurry contains both of these alcohols and many VOC forming bacteria. Environmental drivers like pH, temperature, and oxygenation of the slurry determine both microbial activity and physical processes at which alcohols are produced, metabolized by bacteria, and transferred from liquid to gas phase. The production and emissions of gaseous ammonia and from animal manure is dependent on urea content in urine, the pH and temperature of the manure and urease activity (Monteny et al., 1998; Gay and Knowlton, 2005). Therefore, effective emissions mitigation must address at least one of the main environmental drivers (e.g., pH) to effectively disrupt microbial and enzymatic activity and reduce gas release into the atmosphere (Jongebreur and Monteny, 2001).

Sodium bisulfate (NaHSO4, SBS) is extensively used in the poultry industry to reduce ammonia and bacterial levels in litter. It is also used in the dairy industry to reduce ammonia emissions and bacterial counts in bedding, prevent environmental mastitis, and calf respiratory stress.

From an air quality perspective, the main effect of SBS is the reduction of the manure pH to a level that is not conducive to the propagation of bacteria that form VOCs. Similarly, ammonia formation is markedly inhibited.

Sodium bisulfate (aka Parlor Pal, Jones-Hamilton Co.) is a dry granular acid applied to dairy drylot corrals with tractor driven fertilizer spreaders or by hand application for the control of ammonia, methanol and ethanol.

Mitigation Mechanism:

Sodium Bisulfate is hygroscopic and as ambient moisture is adsorbed into the SBS bead, the component dissolves into its sodium (Na^+), hydrogen (H^+), and sulfate ($SO4^-$) constituents.. The hydrogen ion reduces the pH of the bedding or manure and protonates the ammonia molecule converting it to ammonium ($NH_3 + H^+ \rightarrow NH_4^+$). The ammonium is then bound by the sulfate component forming ammonium sulfate (Ullman et al., 2004). The newly formed ammonium sulfate does not aerosolize but is retained in the manure in its solid form (similar to ammonium sulfate inorganic fertilizer). Theoretically, every 100 kg of SBS binds 14 kg of ammonia based on reaction:
$2\ NaHSO_4 + 2\ NH_4OH \rightarrow (NH_4)_2SO_4 + Na_2SO_4 + 2\ H_2O$

Sodium and hydrogen ions exert synergistic negative pressure on the bacterial populations within the manure decreasing total aerobic population counts by 2-3 logs (Pope and Cherry, 2000) This decrease in bacterial population also serves to further decrease urease concentrations in the manure slurry, leading to additional ammonia reductions (Ullman et al., 2004).

Sodium bisulfate is approved by the FDA for animal and human food use and by the EPA as a surface amendment for ammonia reduction and general bacterial reduction.

Applicability:

Recent dairy emission research conducted in our lab has identified alcohols (methanol and ethanol) as the major VOC group originating from fresh waste and fermented feedstuffs (Shaw et al., 2007; Sun et al., 2008). Effective control of alcohols and ammonia emissions could help meeting regulatory standards, satisfy public concerns, and improve local and regional air quality.

The present study was conducted at the University of California, Davis using surface isolation flux chambers. The dose responses of three potential SBS treatment levels were compared vs. the untreated control on ammonia, amine, and alcohol air emissions from dairy slurry mix (Sun et al., 2008).

Surface application of SBS markedly decreased ammonia and both methanol and ethanol emission fluxs ($P<0.01$) from fresh dairy slurry in a dose-response manner (Table 1). The three-day average ammonia flux from the control (no SBS applied) and the three different SBS surface application levels of 0.125, 0.250, and 0.375 kg m^{-2} were 513.4, 407.2, 294.8, and 204.5 mg hr^{-1} m^{-2}, respectively. The ammonia emission reduction potentials were 0, 21, 43 and 60%, respectively. Methanol and ethanol emissions also decreased with an increase in the amount of SBS applied. The three-day average methanol emissions were 223.7, 178.0, 131.6 and 87.0 mg hr^{-1} m^{-2} for SBS surface application level of 0, 0.125, 0.250 and 0.375 kg m^{-2} with corresponding reduction potentials of 0, 20, 41, and 61%, respectively. Similar emission reduction potentials of 0, 18, 35, and 58% were obtained for ethanol. Sodium bisulfate has been shown to be effective in the mitigation of ammonia and alcohol emissions from fresh dairy slurry.

Table1. Ammonia, methanol, and ethanol emissions and reduction potential from three levels of SBS treated vs. untreated slurry.

	SBS treatment (kg/100 m^2)					
	0	**12.5**	**25**	**37.5**	**SEM**	**P-value**
Ammonia						
Emission rate (mg/hr/m^2)	513.4	407.2	294.8	204.5	18.1	<0.01
Reduction potential (%)	N/A	21	43	60		
Methanol						
Emission rate (mg/hr/m^2)	223.7	178.0	131.6	87.0	6.2	<0.01
Reduction (%)	N/A	20	41	61		
Ethanol						
Emission rate (mg/hr/m^2)	356.4	291.2	232.4	150.8	11.2	<0.01
Reduction (%)	N/A	18	35	58		

Limitations:

Sodium bisulfate is a mineral acid salt. Appropriate measures, as defined by the chemical supplier, should be used during the handling of SBS.

In locations that are sensitive to salt or areas with existing high salt loading in soils, applications of SBS should be considered with care because sodium is one of its components. Application at high rates could cause formation of nitrous oxide.

In addition, SBS must be applied consistently to manure to maintain constant emission reduction as the substance looses its effectiveness over time.

Cost:

Bulk cost of product delivered to the farm is $660.00/ ton. Application at 50 to 75 lb / 1000 ft^2 2X / week equates to costs of between $33.00 to 49.50 / 1000 ft^2 / week. Treatment of heavy use areas, approximately 30% of the total pen area, reduces total pen cost by 70%. Cost / cow assuming 4 cows / 1000 ft^2 of pen area would be $2.48 to $3.71 / week treating only the heavy use areas.

Implementation:
There are no special requirements to implement this program. A fertilizer type spreader is required.

Technology Summary:
Sodium bisulfate application is an acidifier method that can effectively mitigate ammonia and alcohols emissions from dairy slurry.

Additional Resources:
http://www.jones-hamilton.com/products.html

Acknowledgments:
Project support was provided by the California State Water Resources Control Board and the Merced County Department of Environmental Health as well as by Jones-Hamilton Co.

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As published in the proceedings of:
MITIGATING AIR EMISSIONS FROM ANIMAL FEEDING OPERATIONS CONFERENCE
Iowa State University Extension
Iowa State University College of Agriculture and Life Sciences
Conference Proceedings
Sponsored by:
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Reduction of Ammonia Emission from Stored Laying-hen Manure Using Topically Applied Additives: Zeolite, Al⁺Clear, FERIX-3 and PLT

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Species: Poultry (Laying Hens)
Use Area: Manure storage
Technology Category: Chemical Amendments
Air Mitigated Pollutants: Ammonia

Description:

Ammonia (NH_3) emissions from animal feeding operations not only reduce the fertilizer nitrogen (N) value of the manure, but also contribute to environmental pollution. Hence, cost-effective means to reduce NH_3 loss associated with animal housing, manure storage and land application will have positive economic and environmental impacts.

Laying hen manure in commercial egg production is typically either accumulated in the lower level of high-rise (HR) houses or removed from manure-belt (MB) cage houses to a manure storage facility one to seven times a week. Various mechanisms are involved in conserving N in poultry manure during storage, such as immobilization of ammonium (NH_4^+) through addition of easily decomposable, N-poor materials, adsorption of NH_4^+ and NH_3 onto amendments, and regulation of manure pH (Kirchmann et al., 1989).

Mitigation Mechanism:

Natural zeolite [(Na_4K_4) (Al_8Si_{40}) $O_{96}{\cdot}24H_2O$] is a cation-exchange compound that has a high affinity and selectivity for NH_4^+ ions due to its crystalline, hydrated properties resulting from its infinite, 3-dimentional structures (Mumpton et al., 1977). It has been used as an amendment to poultry litter, in anaerobic digesters treating cattle manure, in composting of pig slurry and poultry manure, as an air scrubber packing material to improve poultry house environment. Specific research findings include trapping of > 90% of N loss during 13-d composting of pig slurry by placing 12% (by weight) zeolite and chopped straw mixture in the air stream (Bernal et al.,1993); 44% reduction in NH_3 loss during 56-d composting of poultry manure with a surface application of 38% (by weight) zeolite (Kithome et al., 1999); and 22%–47% reduction in NH_3 emissions over 4-d storage of slurry dairy manure when mixed with 2.5%–6.25% (by weight) zeolite (Milan et al., 1999).

Ammonia volatilization stems from microbial decomposition of nitrogenous compounds, principally uric acid, in poultry manure. Manure pH plays a key role in NH_3 volatilization in that NH_3 generation tends to increase with increasing manure pH. Uric acid decomposition is favored under alkaline (pH>7) conditions, and the effect of uricase—the enzyme that catalyzes uric acid breakdown reaches maximum at pH of 9. Consequently, NH_3 emissions can be inhibited by acidulants that lower manure pH and reduce conversion of NH_4 to NH_3. The acidulants also inhibit bacterial and enzyme activities that are involved in the formation of NH_3, thus reducing NH_3 production. Liquid Al⁺Clear and dry granular Al⁺Clear (aluminum sulfate), FERIX-3 (ferric sulfate) and PLT (sodium bisulfate) are acidulants that, when hydrated, produce hydrogen ions (H^+) that attach to NH_3 to form NH_4. As a result of the reaction, the amount of NH_3 emitting from the manure is reduced, thereby reserving the N content of the manure. Al⁺Clear and PLT had been applied to poultry litter to control NH_3 volatilization (Moore et al., 1995; 1996; Armstrong et al., 2003). FERIX-3 usually is used for industrial and municipal water and wastewater treatment over a wide pH range for color, organics, phosphorous, heavy metal, arsenic and bacteria removal, turbidity, chemical oxygen demand (COD) or biological oxygen demand (BOD) reduction and enhanced coagulation.

Applicability:

Manure in MB houses drops onto a belt beneath cages and is frequently removed from the house, say, 1 to 7 times per week. The removed manure could be transported and stored in manure storage before it is land-applied or composed. NH_3 emission from manure storage primarily depends on the manure handling practices. The manure surface exposed to the air should be limited to control the NH_3 emission. The following practices are suggested to reduce emissions: 1) reduce the surface area of manure piles; 2) keep adding new manure on the old manure pile; 3) keep the temperature of manure storage low if possible. In addition, using topically applied additive can mitigate the NH_3 emission in the manure storage. This publication covers the testing results of using zeolite, Al⁺Clear, FERIX-3, and PLT as the agents of topical application on nearly fresh laying-hen manure in storage.

Limitations:

Since Al^{+}Clear, FERIX-3 and PLT all have low pH, care must be taken in the material handling (i.e., wearing gloves and eye protection) and to reduce potential corrosion to building components.

Cost:

Table 1 lists the cost comparison of dry Al^{+}Clear, FERIX-3 and PLT, with different application rates. Table 2 lists the costs of the 48.5% liquid Al^{+}Clear and Zeolite. Three application rates for liquid and dry Al^{+}Clear, FERIX-3, PLT, and Zeolite were tested. Since the NH_3 emission reduction from two of the three application rates for Al^{+}Clear, FERIX-3, and PLT had no difference, the costs of higher application rate are not listed for the comparison. The costs listed do not reflect the delivery costs. Because these additives could be applied with the same or similar methods, the comparison does not include the application cost either. The costs of the additives are based on the 50 lb/pack prices of 2008.

Ability of the additives to reduce emissions decreases over time. The costs of the topical application of the agents at end of the 7^{th} day was as following: A) 1.56, 1.81 or 1.83 cent/ft^2-10% NH_3 reduction, respectively, for zeolite applied at 0.6, 1.3, or 1.9 lb/ft^2 (3.1, 6.3, or 12.5 kg m^{-2}); B) 0.25 or 0.36 cent/ft^2-10% NH_3 reduction, respectively, for liquid Al^{+}Clear applied at 0.2, or 0.4 lb/ft^2 (1, or 2 kg m^{-2}) of manure surface area; C) 0.36 or 0.49 cent/ft^2-10% NH_3 reduction, respectively, for dry granular Al^{+}Clear applied at 0.1 or 0.2 lb/ft^2 (0.5 or 1.0 kg m^{-2}); D) 0.46 or 0.42 cent/ft^2-10% NH_3 reduction, respectively, for FERIX-3 applied at 0.1 or 0.2 lb/ft^2 (0.5 or 1.0 kg m^{-2}); and E) 0.45 or 0.60 cent/ft^2-10% NH_3 reduction, respectively, for PLT applied at 0.1 or 0.2 lb/ft^2 (0.5 or 1.0 kg m^{-2}).

Table 1. Comparison of costs and NH_3 emission reductions (mean ± standard deviation) of topical application of Granular Al+Clear, FERIX-3, PLT and Zeolite at different rates on reduction of ammonia emission from stored laying hen manure

		PLT		FERIX-3		Granular Al^{+}Clear	
Appl.Rate	kg/m^2	0.5	1	0.5	1	0.5	1
	lb/ft^2	0.1	0.2	0.1	0.2	0.1	0.2
Cost	Cent per ft^2	2.5	4.9	1.9	3.8	2.3	4.5
	$ per m^2	0.26	0.53	0.21	0.41	0.24	0.48
Cost, cent/ft^2/10% of NH_3 reduction	Day 1	0.29	0.60	0.22	0.43	0.26	0.50
	Day 2	0.28	0.58	0.22	0.43	0.25	0.50
	Day 3	0.28	0.57	0.22	0.44	0.25	0.50
	Day 4	0.30	0.56	0.22	0.44	0.26	0.50
	Day 5	0.34	0.56	0.25	0.44	0.27	0.50
	Day 6	0.38	0.56	0.32	0.43	0.30	0.49
	Day 7	0.45	0.60	0.46	0.42	0.36	0.49

Table 2. Costs and NH_3 emission reductions (mean) of topical application of Liquid Al+Clear and Zeolite at different rates on reduction of ammonia emission from stored laying hen manure

		Liquid Al^{+}Clear			Zeolite	
Appl.Rate	kg/m^2	1	2	3.1	6.3	12.5
	lb/ft^2	0.2	0.4	0.6	1.3	1.9
Cost	cent/ft^2	1.6	3.2	5.6	11.2	16.8
	$/m^2	0.17	0.34	0.6	1.2	1.8
Cost, cent/ft^2/10% of NH_3 reduction	1	0.17	0.35	0.85	1.23	1.75
	2	0.17	0.34	1.04	1.32	1.73
	3	0.19	0.34	1.19	1.45	1.73
	4	0.20	0.34	1.30	1.56	1.73
	5	0.21	0.34	1.40	1.65	1.75
	6	0.23	0.34	1.47	1.72	1.79
	7	0.25	0.36	1.56	1.81	1.83

Implementation:

Eight emission vessels were designed and built for the study (fig. 1). The vessels were placed in an environmentally-controlled room that was kept at a constant temperature of 23°C (73°F). A flow rate of 3 LPM was introduced into each vessel, resulting in an air exchange rate of 11 air changes per hour (ACH). During each trial, new batch of hen manure was collected and mixed before it was randomly assigned to the eight emission vessels. Manure samples with an initial weight of 2.5 kg were used as the experimental units. The 2.5 kg sample was placed in a 3.8-liter (1-gal) container (surface area of 0.02 m^2) that was further placed inside the 19-liter (5-gal) emission vessel.

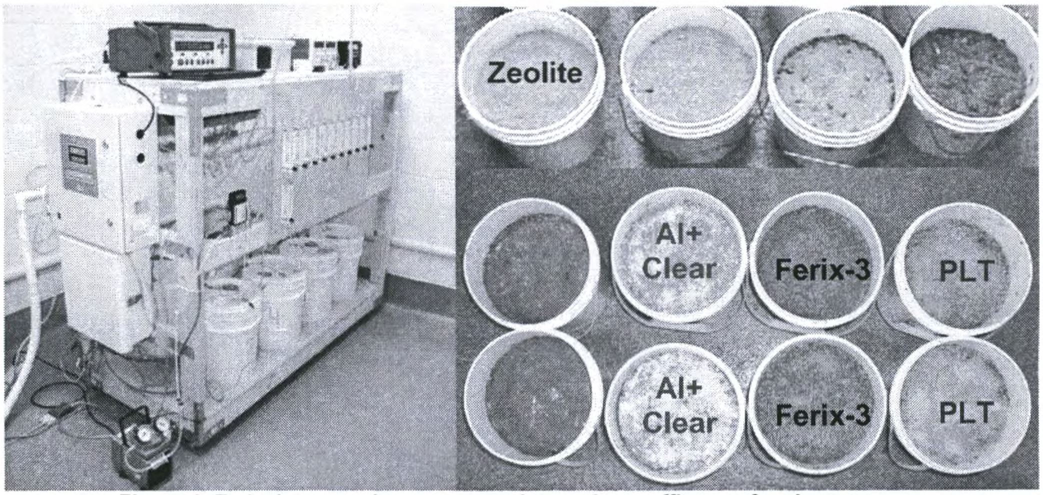

Figure 1. Emission vessels system used to evaluate efficacy of various manure treatment agents to reduce ammonia emissions from manure storage.

Two vessels were used as controls (i.e., no additives). The five additives tested included natural zeolite, two forms of Al⁺Clear (48.5% liquid and dry granular), FERIX-3, and PLT. The additives were topically applied to the manure samples at three dosages of low, medium, or high that corresponded to 2.5%, 5% or 10% of the manure weight (3.1, 6.3 or 12.5 kg/m^2 manure surface area) for zeolite; 1, 2, or 4 kg/m^2 manure surface area for liquid Al⁺Clear; and 0.5, 1.0, or 1.5 kg/m^2 for granular Al⁺Clear, FERIX-3, and PLT. Two or three trials were conducted to obtain four or six replicates of each treatment. Each trial lasted 7 days.

The NH_3 emission reductions with the medium dosages were in the range of 62% to 93% while NH_3 emission reductions with the low dosages varied from 36% to 82% (Table 3). The NH_3 emission reductions with high dosage were up to 94% during 7-d period. The result shows that there were no significant difference between the high dosage and medium dosage for liquid and granular Al⁺Clear, FERIX-3, and PLT after the 7-d storage period (P=0.5) (Table 3).

Table 3. NH_3 emission reductions (mean ± standard deviation) of topical applied Zeolite, liquid Al⁺Clear, granular Al⁺Clear, FERIX-3 and PLT at different rates at the end of the 7-d storage period

Additives	Application dosage		
	Low	Medium	High
Zeolite	36±10% [a]	62±7% [b]	92±2% [c]
48.5% Liquid Al⁺Clear	63±11% [a]	89±5% [b]	94±2% [b]
Granular Al⁺Clear	81±10% [a]	93±1% [b]	94±2% [b]
FERIX-3	82±5% [a]	86±5% [b]	87±1% [b]
PLT	74±8% [a]	90±3% [b]	92±1% [b]

Table 4. Comparison of NH_3 emission reductions (mean ± standard deviation) of topical applied granular Al⁺Clear, FERIX-3 and PLT at different rates at the end of the 7-d storage period

		PLT		FERIX-3		Granular Al⁺Clear	
Appl. Rate	kg/m^2	0.5	1	0.5	1	0.5	1
	lb/ft^2	0.1	0.2	0.1	0.2	0.1	0.2
Day	1	86±2%	81±3%	87±3%	89±2%	89±1%	91±1%
	2	91±1%	85±2%	88±3%	89±1%	90±1%	91±1%
	3	89±1%	87±3%	88±3%	87±1%	91±1%	89±1%
	4	82±5%	88±3%	86±1%	86±2%	90±1%	89±1%
	5	74±10%	88±2%	77±6%	86±2%	87±2%	90±2%
	6	65±14%	87±2%	60±16%	88±1%	77±5%	91±2%
	7	56±18% [a]	81± 2% [b]	42±26% [a]	90±1% [b]	63±8% [a]	92±3% [b]

The granular Al^+Clear, FERIX-3, and PLT were selected to compare the NH_3 emission reduction rate over a 7-d storage period. In each trial, two vessels were used as controls and two dosages (0.5 and 1.0 kg/m^2) of Al^+Clear, FERIX-3, and PLT were applied to the remaining six vessels. During the first 3-d period, there was no difference in NH_3 emission reduction rates among all applications. NH_3 emissions of the low application rate vessels started to increase on 4th, 4th, and 5th d for PLT, FERIX-3, and Al^+Clear, respectively (fig. 2). At the end of the 7-d period, the NH_3 emission reduction rates from all vessels with 1.0 kg/m^2 application rate were the same (88%), and they were significantly higher than the reduction rates with the 0.5 kg/m^2 rate (Table 4). There was no significant difference in the reduction rates among the three additives with 0.5 kg/m^2 application rate after 7-d period.

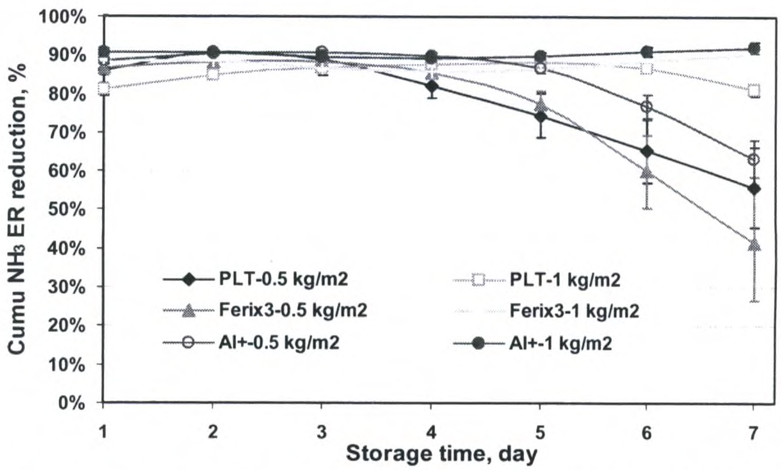

Figure 2. Ammonia emission reductions of ventilated storage of laying hen manure with different rates of topical application of granular Al^+Clear, FERIX-3, and PLT.

Technology Summary:

Ammonia emission from manure storage may be controlled by using physical, chemical and/or biological methods. In this study, five treatment agents, including zeolite, 48.5% liquid Al^+Clear (aluminum sulfate), granular Al^+Clear (aluminum sulfate), granular FERIX-3 (ferric sulfate), and PLT (sodium bisulfate) were topically applied to stored nearly fresh laying-hen manure. Each agent was tested at three application rates, i.e., low, medium and high. The results show that there were no significant difference between the high and medium dosages for Al+Clear, FERIX-3, and PLT after the 7-d storage period. Reduction of NH_3 emission by the topical application of the agents over a 7-day manure storage/testing period was as following: A) 36%, 62% or 92%, respectively, for zeolite applied at 3.1, 6.3, or 12.5 kg m^{-2} (0.6, 1.3, or 1.9 lb/ft^2); B) 63% or 89%, respectively, for liquid Al^+Clear applied at 1, or 2 kg m^{-2} (0.2, or 0.4 lb/ft^2) of manure surface area; C) 56% or 81% respectively, for dry granular Al^+Clear applied at 0.5 or 1.0 kg m^{-2} (0.1 or 0.2 lb/ft^2); D) 42% or 90%, respectively, for FERIX-3 applied at 0.5 or 1.0 kg m^{-2} (0.1 or 0.2 lb/ft^2); and E) 74% or 90%, respectively, for PLT applied at 0.5 or 1.0 kg m^{-2} (0.1 or 0.2 lb/ft^2).

Additional Resources:

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Acknowledgments:

Funding for this study was provided in part by the U.S. Poultry and Egg Association and is acknowledged with gratitude. The experimental equipment was procured with partial funds from the College of Agriculture and Life Sciences Air Quality Research Initiative.

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As published in the proceedings of:
MITIGATING AIR EMISSIONS FROM ANIMAL FEEDING OPERATIONS CONFERENCE
Iowa State University Extension
Iowa State University College of Agriculture and Life Sciences
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Iowa Pork Producers Association
U.S. Pork Center of Excellence

Gas Impermeable Film and Sheet for Control of Methane and Odors in Agricultural Applications

G. Kolbasuk
Raven Industries, Engineered Films Division, Sioux Falls, South Dakota, USA

Species: Swine, Dairy, Beef, and Poultry
Use Area: Manure Storage, Manure Treatment
Technology Category: Cover
Air Mitigated Pollutants: Methane, ammonia, odor, volatile organic carbon compounds, fumigants.

Description:

For many years, food packaging has incorporated barrier layers to contain odors, flavors, oils and moisture along with the food contents while excluding contamination and oxygen. Until recently, agricultural films and geomembranes were monolithic structures employing only a single polymer or blend. Recent advances in extrusion and lamination equipment allow the incorporation of barrier layers in large scale agricultural structures and operations such as floating covers over animal waste storage, containment geomembranes for biogas generation, silage storage and fumigation films.

Coextruding a thin layer of ethylene vinyl alcohol (EVOH) in a linear low density polyethylene (LLDPE) geomembrane dramatically reduces the permeability to a wide range of gases and volatile organic carbon molecules including: methane, ammonia, carbon dioxide, oxygen, aromatic hydrocarbons, aliphatic hydrocarbons, methyl bromide and most odorous compounds. Methane permeabilites for four geomembranes are given below.

Table 1. Methane Permeability (cc/(m^2·day))

PVC 0.76 mm (30 mils)	LLDPE 1.0 mm (40 mils)	HDPE 1.0 mm (40 mils)	Barrier LLDPE 0.5 mm (20 mils)
900	690	300	<1

Mitigation Mechanism:

Geomembranes used as covers act primarily as a barrier against bulk air and gas movement. This serves to contain most gases generated under the cover and to reduce the amount of odor carrier away from the site. Figure 1 is an example of such a cover being used over a manure storage facility to collect gas. More sophisticated geomembrane structures combining multiple polymers with different barrier properties can enhance the performance of the geomembrane by reducing the permeability to many gases and odors.

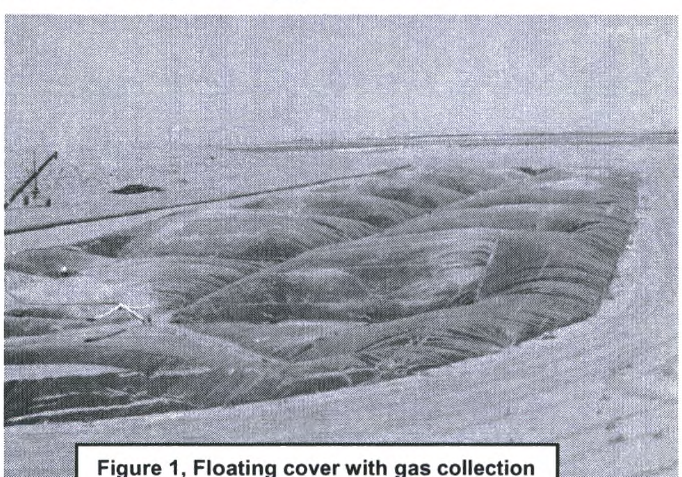

Figure 1, Floating cover with gas collection

The structure discussed in this paper is a simple five layer coextrusion used by itself or laminated into a thicker geomembrane with scrim reinforcement. It consists of LLDPE or other types of polyolefin on the two outside surfaces with a core layer of EVOH or nylon. LLDPE and EVOH do not bond to each other and requires a "tie layer" between the two.

Polyethylene is used on the outside layers as the primary polymer because of the ease of extrusion, the toughness it adds to the product, the ease in which it can be welded and because of its relatively low cost. Since polyethylene is a non-polar molecule, it is a good barrier to polar molecules such as water, alcohol and dissolved salts. Unfortunately, the amorphous part of its structure readily accepts non-polar molecules such as methane, oxygen, radon, benzene and a large number of other hydrocarbons. The permeability of polyethylene is too high to be used as an oxygen barrier for food, an oil barrier for packing or a gasoline barrier for fuel tanks.

EVOH and nylon are polar and more crystalline, making them a better barrier to non-polar solvents and gases than polyethylene. Figure 2 illustrates this with the oxygen permeability of several packaging polymers. The y-axis is a log scale and shows LDPE to be more than 1000 times more permeable to oxygen than EVOH. While this table hints that EVOH can be a much better barrier to other chemicals, the oxygen permeability can not be used to calculate the permeability of other non-polar gases and solvents since there are other reactions related to molecule size and chemical interactions that affect the permeability.

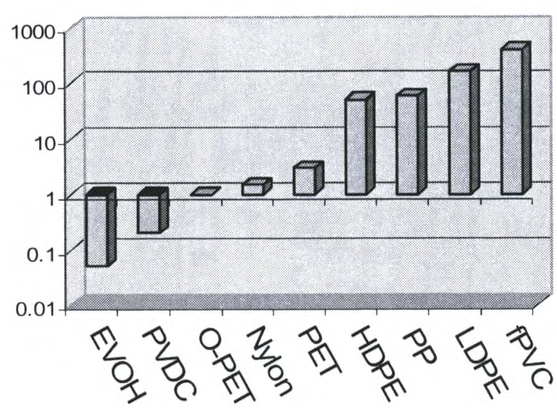

Figure 2, Oxygen Permeability
(cm^3*mm/m^2*day*atm)

Applicability:

This mitigation technology has several agricultural applications. The oxygen data shown in figure 2 indicate the effectiveness of a silage film or bag with an EVOH layer in keeping silage from spoiling.

Chemical pollution from fumigants is another agricultural application. Broadcast flat fumigation is a process by which large fields are treated to kill insects, nematodes, weeds and undesirable microorganisms. Strawberry fields in the southwest United States are commonly treated prior to planting. The process shown in figure 3 involves injecting the fumigant into the ground and immediately covering the applied area with a plastic film to help retain the fumigant. One edge of the film in embedded into the ground and the other is glued to the previously treated and covered area.

The preferred fumigant has historically been methyl bromide because of its effectiveness. Methyl bromide has come under fire because of its toxicity and because it is known to contribute to the depletion of the ozone layer. It has been banned internationally but it still being used by exception, where there is a critical application and for which no suitable equivalent fumigant is available.

HDPE film is typically used to cover the treated area. Figure 4 compares the retention of the methyl bromide in the soil when covered by an HDPE film to that when covered by a Totally Impermeable Film (TIF). The TIF, not actually totally impermeable, is a polyethylene film with a 0.1 mil thick core layer of EVOH. The lower permeability of the TIF film allows the methyl bromide to be used at much lower concentrations and still be effective. The data presented here is from unpublished research in progress, Steve Fennimore, University of California, Davis.

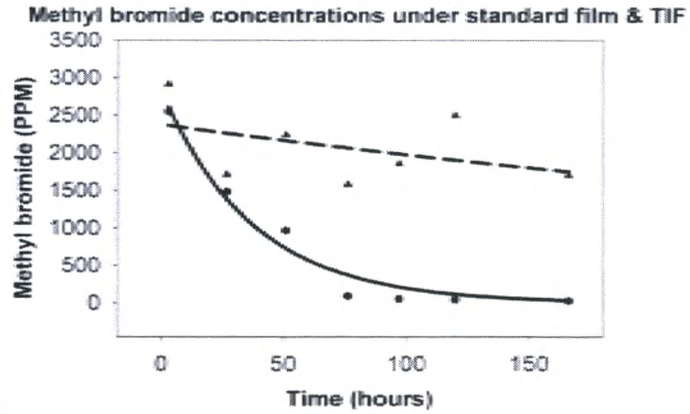

Figure 4, Methyl Bromide under standard HDPE film (solid line) and LL / EVOH film (dashed line)

Animal waste storage has become a major issue as the size of animal feed lots and commercial farms grow in size. One solution to control odor is to move the manure into holding ponds covered by floating covers. Polyethylene covers help control the odor but odor readily permeates and penetrates the cover. As in food packaging applications where barrier films contain odors, so can an Absolute Barrier Geomembrane be an effective odor barrier in covers. The following study of the permeability of several geomembranes illustrates the improvement seen when a thin layer of EVOH is included in a polyolefin geomembrane.

	LLDPE	LL/PA	LL/EVOH
Benzene	4.5	25	40,000
Toluene	6.5	37	55,000
Ethylbenzene	9.0	45	100,000
m/p-Xylenes	7.5	40	105,000
o-Xylenes	6.0	30	70,000

Figure 5, Relative Diffusion Properties Compared to PVC (higher value represents lower permeability)

Rebecca McWatters, under the direction of Dr. Kerry Rowe, has been conducting diffusion tests on several geomembranes. They included a 0.76 mm (30 mil) PVC, a 0.5 mm (20 mil) linear low density polyethylene, a 0.36 mm (14 mil) LLDPE containing a core barrier layer of polyamide (LL / PA) and a 0.5 mm (20 mil) LLDPE containing a core layer of EVOH (LL / EVOH). Each of the materials was challenged with an aqueous solution containing BTEX, a mixture of benzene, toluene, ethylbenzene and xylenes in concentrations representative of what would be found in a landfill. Details of the procedure are given in the referenced 2007 paper. The current work is not yet complete and will be published in the future. The permeability testing of the LL / EVOH is ongoing and the values given in the table are estimates based on the data collected at the time of this writing.

Figure 5 contains the diffusion coefficient of the PVC geomembrane divided by the diffusion coefficient of the tested geomembrane, normalized for thickness. The higher the value in the table, the lower the permeability. In order of permeability, from highest to lowest, PVC > LL > LL / PA > LL / EVOH. The inclusion of EVOH dramatically reduces the permeability of BTEX through the LL.

Limitations:

EVOH owes some of its impermeability to its high level of crystallinity. This makes EVOH more rigid than many of the softer polymers used in geomembranes. While EVOH has ultimate tensile elongation in excess of 200% and is flexible when in relatively thin layers, it is not elastic and should not be used as part of an elastomeric geomembrane.

Cost:

EVOH is more expensive than polyethylene, the equipment needed to processes it is more expensive and any scrap that is generated has little or no value. As such, the cost of a membrane containing EVOH is 30% to 50% more expensive than one without the EVOH. However, cost savings in fumigation applications resulting from using less fumigants more than offset the cost of the EVOH. In the case of covers, since the cost of the geomembrane is a small part of the finished installation, the additional cost of the barrier geomembrane is small when expressed as a percentage of the project.

Engineered floating covers with ballasted weight systems, gas extraction systems and a rainwater removal systems costs vary greatly. For a waste lagoon of about 1/2 acre in size, the cover system can cost from $150,000 to $200,000. Addition of the barrier layer to the geomembrane adds less than $5,000.

Implementation:

Implementing the use of barrier films and geomembranes in agricultural applications is no different than using films or membranes without the barrier layer.

Technology Summary:

The incorporation of layered technology that includes high barrier materials such as used in food packaging greatly reduces the permeability of films and membranes to a variety of gases, pollutants and odor. Applications include containment liner is bioreactors, floating covers over waste lagoons, silage storage and fumigation films. Polyolefin products incorporating barrier layers can be used the same as those without. The barrier products result in enhanced odor and pollution control and can be more economical in applications such as fumigation.

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MITIGATING AIR EMISSIONS FROM ANIMAL FEEDING OPERATIONS CONFERENCE
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A Review of Permeable Cover Options for Manure Storage

R. Burns and L. Moody
Iowa State University

Species: Beef, Dairy & Swine
Use Area: Manure Storage
Technology Category: Manure Cover
Air Mitigated Pollutants: Ammonia, Odor, Hydrogen Sulfide

Description:

Covers have been demonstrated to provide effective odor and air emissions control for manure storage structures. Impermeable covers made from flexible synthetic materials provide excellent odor and emissions control, but typically have a high capital cost requirement. Part of the cost associated with the installation of an impermeable cover is the infrastructure required to collect and remove gases from underneath the cover as well as to collect and remove rain water that falls onto the cover. Additionally manure storage structures that are emptied on an annual or semi-annual basis, and hence have a large change in manure level, also require special installation considerations to allow an impermeable synthetic cover to travel up and down as the stored manure level changes.

Permeable covers provide an alternative to impermeable synthetic covers. Permeable covers will typically not provide as high of a level of odor control as a properly installed and maintained impermeable covers, but the initial capital cost for permeable covers is typically lower. Additionally permeable covers are much simpler to maintain than impermeable covers since they do not require gas or rain water collection systems since gases are allowed to migrate through the cover and rainwater will infiltrate through the cover into the manure storage. Also, no infrastructure to raise and lower the cover as the manure level changes within the storage structure is typically required with permeable covers, since they are floated on the stored manure's surface.

Permeable covers have been successfully constructed from a variety of materials including straw, cornstalks, Light Weight Expanded Clay Aggregate (LECA), ground rubber, plastic beads and geotextile materials. Other materials such as *Vermiculite*, *Perlite* and various oils have been tested, but found to provide unsatisfactory performance (MAFF, 2000).

Odor control effectiveness ranging from 40 – 90% has been reported for permeable covers made from various materials. Straw permeable covers are reported to have an odor control effectiveness of 40% when applied in a 4 inch depth and 90% at a 12 inch depth. Geotextile covers are reported to have a odor control effectiveness ranging from 40 – 60%, while a floating LECA cover is reported to have a 90% odor control effectiveness (Nicolai, et. al, 2004). Ammonia control effectiveness is typically reported to be lower than odor control while hydrogen sulfide control is usually higher than odor control when comparing the same materials.

Mitigation Mechanism:

Permeable covers mitigate air emissions from manure storages through two mechanisms. First, permeable covers provide a physical barrier that prevents direct contact of air to the stored manure's surface. This reduces the transfer of gaseous compounds into the atmosphere Additionally, many permeable cover materials provide an environment that promotes the growth of aerobic bacteria in the floating cover material. These aerobic bacteria can oxidize many of the odorous compounds released from the stored manure as they pass through this aerobic interface. Figure 1 shows a simple diagram that illustrates the aerobic zone that can be developed with some permeable cover materials. Materials such as straw, LECA, or other materials that allow air to penetrate the floating cover layer and provide adequate moisture and surface area to allow a population of aerobic bacteria to develop can provide this increased odor reduction effect.

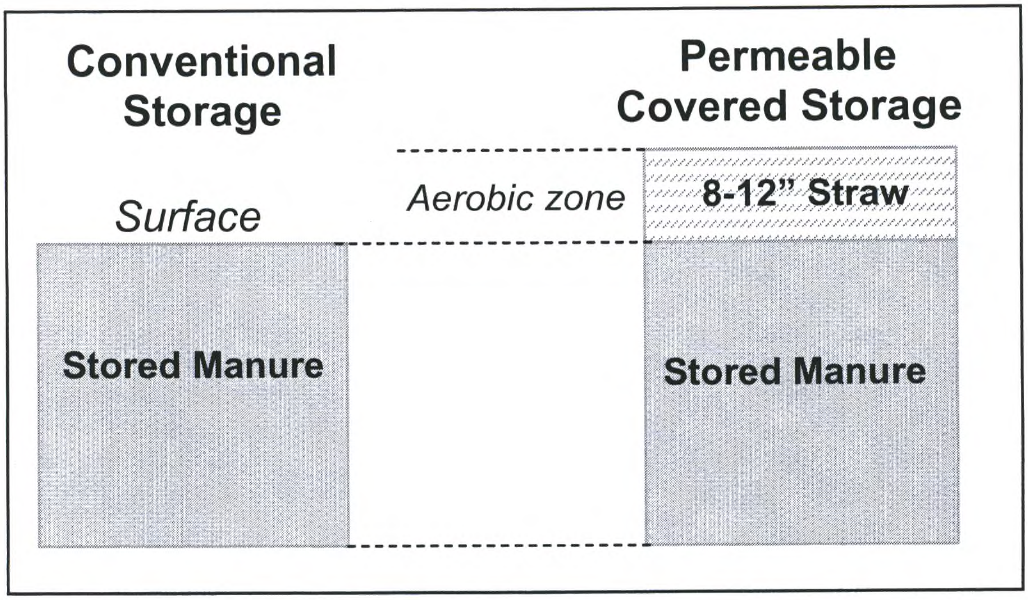

Figure 1. Cross Section of Manure Storage Structure Demonstrating Aerobic Zone Provided by Some Permeable Cover Materials

Applicability:

Floating permeable covers can be used to cover manure slurries of any species. It should be noted however that because these covers float on top of the manure's surface, they will usually have a longer working life when used with manure slurries that have a relatively high total solids content. Research conducted by the Silsoe Research Institute in the United Kingdom directly addressed the impact of both rainfall and manure total solids content on cover longevity. The results of this research show that dry straw floats very well on manure slurries, but that when rained on, the rate at which the straw sinks dramatically increases, and that the rate at which the straw sinks increases as the manure slurry total solids content decreases.

While straw covers are reported as being impractical on manure storages with over two acres of surface area (Nicolai, et. al, 2004), examples of straw covers on manure storage lagoons as large as four acres can be found. The authors agree however that the larger the manure storage structure the more difficult a uniform application of materials such as straw becomes.

Straw

Straw is the lowest cost permeable cover material commonly utilized and has a typical installed cost of $0.10 per square foot. While a straw cover has a low initial cost, it also has a short lifespan as a cover. Straw covers floated on manure slurries can be expected to remain floating on the manures surface for two to six months. The length of time that a straw cover will continue to float is a function of rainfall and total solids content of the manure slurry the cover is floated on. Research has demonstrated that straw floated on water and exposed to rainfall sank in less than seven days, while straw floated on an eight percent total solids cattle slurry and exposed to rainfall maintained 80 percent surface coverage for 40 days. Straw floated on a beef manure slurry with four percent total solids and no exposure to rainfall provided an 80 percent surface coverage for 40 days, while straw floated on a beef manure slurry with eight percent total solids and no exposure to rainfall provided a 100 percent surface coverage for the full length of the 77 day test period (MAFF, 2000). At some point however, a straw cover will sink, and when this occurs it increases the difficulty of agitating and land applying the stored manure. Given the short-lived nature of a straw cover and the increased agitation and pumping difficulties that must be dealt with, straw covers are best used as a short-term odor control measure that can be implemented to control an unexpected or severe odor problem associated with a manure storage system. If long-term odor or emissions control is needed, a material with a longer lifespan than straw should be selected. A large round bale of straw can be expected to cover approximately 500 square feet of surface area when chopped and applied to a manure storage structure at a 12 inch depth (Nicolai, et. al, 2004). The cost of such a cover can be easily calculated based on the current price of straw in the region where the cover will be installed. For instance, if a 6 foot diameter roll of straw costs $40 per roll and 500 square feet could be covered per roll, the material cost for the cover would be $0.08 per square foot. Permeable straw covers are typically chopped and blown onto the manure storage surface. Figure 2 shows a straw cover one week after installation on an earthen manure storage structure.

Figure 2. Permeable Straw Cover Installed on an Earthen Manure Storage Structure

LECA

Lightweight Expanded Clay Aggregate, or LECA, is produced by heating a pre-treated clay with high plasticity in a rotary kiln, followed by burning the material at 1100 degrees C to produce the final LECA product. LECA is typically used as a lightweight aggregate construction material, but has been demonstrated to work very well as a permeable manure cover for both odor and ammonia control. Research has shown LECA to provide 90% odor control and ammonia control ranging from 65-95% (MAFF, 2000, Nicolai, et. al, 2004). LECA applied two to four inches deep on swine manure storage tanks in Iowa has been demonstrated to have a more than a 10 year lifespan, and has provided excellent odor control. While LECA makes an excellent permeable cover, the initial capital cost is more expensive than many other permeable cover materials, with a reported cost of $1.75 per square foot installed (Nicolai, et. al, 2004). Availability within the United States is also a potential issue with LECA. While LECA is produced in many areas of the world including Denmark, the United Kingdom, Iran, Italy and Spain, no producer in the United States is currently known to supply LECA as a permeable manure cover material. Because of this, a large portion of the cost reported with LECA use in the United States as a permeable manure cover is derived from the shipping cost to import the LECA. Figure 3 shows a LECA permeable cover in-place on a swine manure storage tank.

Ground Rubber

Ground rubber was tested as a permeable manure cover material and reported to work well over a four month test period (Koppolu et. al, 2005). Koppolu tested a three inch layer of fine ground rubber and found that it reduced odor from stored swine manure from 77 to 99 percent in a six week laboratory study. In the lab study hydrogen sulfide emissions were always below detectible limits from the test tanks, so no hydrogen sulfide emissions control could be tested, and ammonia control was found to be inconsistent in nature. Field tests were conducted in which a two inch ground rubber cover was tested on a swine manure storage structure over a four month period. The fine ground rubber cover was reported to work well in field tests and provide substantial odor, ammonia and hydrogen sulfide reductions over the four month trial period. The rubber used in the tests was an industrial waste by-product from tire recycling and no cost information on the material was provided by Koppolu.

Geotextile

Geotextile floated on manure slurries has been tested for odor and ammonia control effectiveness, but mixed results have been reported. Studies have reported that geotextile covers provide from 40 to 65 percent odor control and from 30 to 90 percent hydrogen sulfide control, and limited ammonia control from stored manure (Nicolai, et. al, 2004). The effectiveness of geotextile covers at mitigating odor and gas emissions from stored manure have been reported to decrease with time, with significant decreases in performance occurring by the second year of use (Clanton, 2001, Bicudo, et. al, 2002). Geotextile covers have been tested on earthen lagoons and holding ponds. Because the geotextile cover is usually anchored to the side of the pond, difficulties can arise when the manure storage level changes during manure removal events. Bicudo reported that after manure agitation and pumping in the earthen manure storages used for the study, that the geotextile covers stayed at the bottom of the manure storage structures, and that snowfall onto the cover in the winter resulted in the cover sinking into the manure. He reported that in the spring the covers at all three test sites had 90% or more of their surface areas submerged below the manures surface (Bicudo, et. al, 2002). This suggests that geotextile covers, much like synthetic impermeable covers must be installed with the infrastructure required to keep the cover intact and afloat during periods of change in the manure level within the storage. Geotextile covers without supporting infrastructure are reported to cost around $0.25 per square foot. Covers that combine geotextile with either closed cell foam or straw have been shown to function better than geotextile alone as a manure cover.

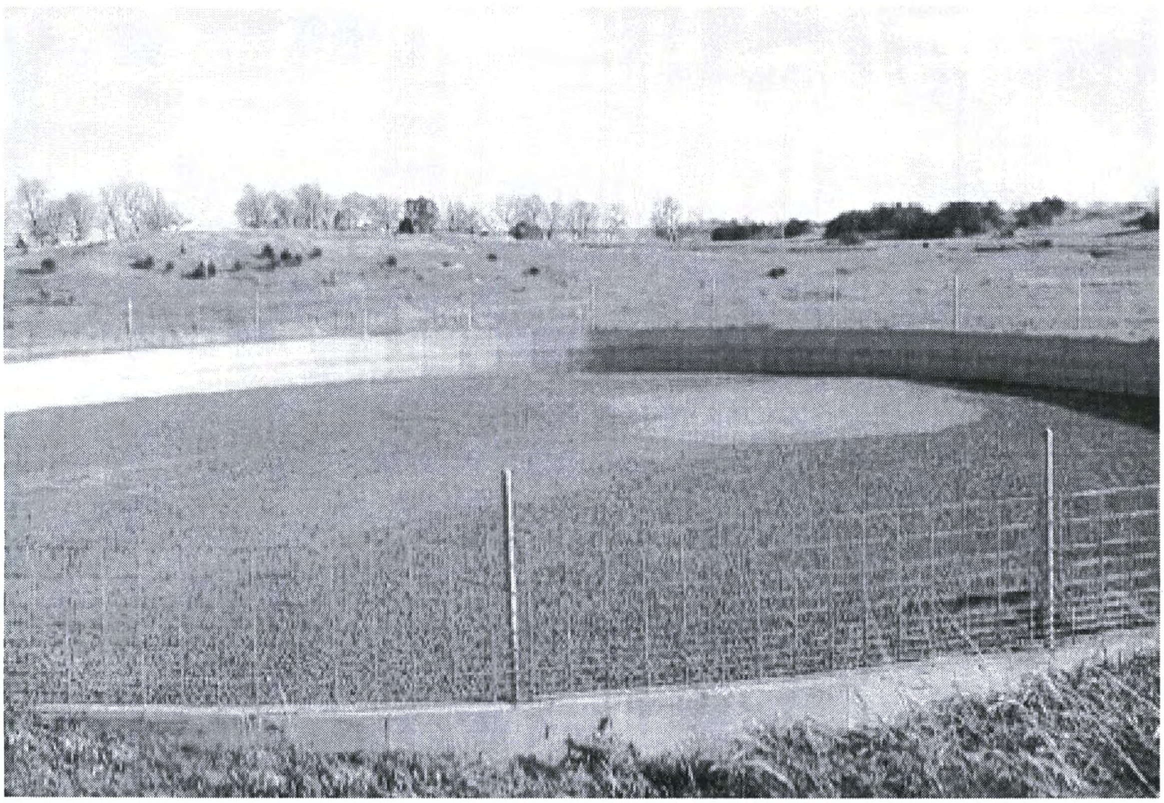

Figure 3. LECA Cover on A Concrete Swine Manure Storage Tank

Mineral Granules

Vermiculite and *Perlite* have both been tested as permeable cover materials and both were found to provide unsatisfactory results. While *Vermiculite* and *Peralite* are both low density materials, they were found unsuitable for use as permeable covers for different reasons. The *Vermiculite* absorbed water and then sank into the manure slurry, while the *Perlite* was easily blown away in windy conditions (MAFF, 2000).

Oils

Oils such as rape seed oil and used cooking oil have been tested as potential permeable cover materials, but neither was found acceptable. Researches testing these oils found that because they are biodegradable, they began to breakdown when placed on manure slurries and generated increased methane emissions in the process. Also, as they were biodegraded they also lost their surface integrity (MAFF, 2000).

Limitations:

Some permeable cover materials, such as straw or cornstalks, have very short effective lives. A straw cover can be expected to last from two to six months before sinking into the manure slurry. Also, once a permeable cover material such as straw or cornstalks sink, they must be dealt with during manure agitation and pump-out and will increase the difficulty of this task.

While material such as LECA provide a long-term permeable cover with an expected working life of greater than 10 years, they are also much more expensive to purchase initially than shorter lived permeable cover materials. The LECA cost of $1.75 per square foot reported by Nicolai approaches the cost of synthetic impermeable liner materials with 20 year life-spans.

The size of the manure storage structure can also become a limitation in that it can become impractical to place materials such as straw and LECA on the surface of very large manure storage structures. For example, Nicolai suggests that it is impractical to apply a straw cover to manure storage structures with greater than two acres of surface area.

Since permeable covers allow gases to migrate through the cover, there is no opportunity to collect biogas that may be generated within the manure storage. Similarly since direct rainfall onto the cover will infiltrate into the manure storage, the additional storage volume to store this rainfall must be included in the manure storage design volume.

Cost:

Permeable covers can provide reductions in odor, ammonia and hydrogen sulfide emissions from manure storage facilities. A wide variety of organic and manmade materials have been utilized to construct permeable covers with variable results and costs ranging from $0.10 to $1.75 per square foot installed. Straw is the least cost permeable cover material with an approximate cost of $0.10 per square foot installed. Longer lasting materials such as LECA have installed costs that can approach the cost of impermeable synthetic cover materials.

Implementation:

Permeable cover materials are typically floated on the stored manure surface and shield manure from direct contact with the atmosphere and can also provide an aerobic zone that manure gases must pass through when released. Permeable covers can be used with earthen, concrete and steel manure storage systems and with slurry manures generated by swine, dairy and beef animals. Installation is a relatively simple process in that the cover materials are either blown or placed directly on the stored manure's surface.

Technology Summary:

Several permeable cover materials have been demonstrated to provide effective odor and air emissions control for manure storage structures. Permeable covers provide an alternative to impermeable synthetic covers that are simpler and less expensive to install. Permeable covers have been successfully constructed from a variety of materials including straw, cornstalks, Light Weight Expanded Clay Aggregate (LECA), ground rubber and geotextile based covers.

Odor control effectiveness ranging from 40 – 90% has been reported for permeable covers made from various materials. Straw permeable covers are reported to have an odor control effectiveness of 40% when applied in a 4 inch depth and 90% at a 12 inch depth, while a floating LECA cover is reported to have a 90% odor control effectiveness (Nicolai, et. al, 2004). Geotextile covers are reported to have a odor control effectiveness ranging from 40 – 60%, but are also reported to lose their effectiveness over time. For all of the permeable cover materials listed, ammonia control effectiveness is typically reported to be lower than odor control while hydrogen sulfide control is usually higher than odor control when comparing the same materials.

The expected lifetime of a permeable cover varies with the material used to construct the cover. Straw covers typically have the lowest initial installation cost, as well as the shortest working life. Lightweight Expanded Clay Aggregate covers have one of the more expensive initial installation costs, but are also reported to have a long working life.

Additional Resources:

Covers for Manure Storage Units http://agbiopubs.sdstate.edu/articles/FS925-D.pdf

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A New Geosynthetic Cover for Odor Control and BioGas Collection

Andrew Mills
Layfield Environmental Systems

Species: Dairy, Beef, Swine
Use Area: Manure Storage, Manure Treatment
Technology Category: Cover
Air Mitigated Pollutants: Ammonia, Methane, Hydrogen Sulfide, Volatile Organic Carbon, Odor

Description:

Geosynthetic covers have been used for a number of years for the control of odors from liquid manure ponds. Current projects are concentrating on large biogas collection covers that require skilled installation and significant installation time. This paper introduces a new prefabricated impermeable manure containment cover that is designed to make smaller projects economical. The cover is adaptable for a number of manure storage applications including ponds with variable liquid levels (slurry storage) and ponds with constant liquid levels (biogas collection).

Mitigation Mechanism:

It has been reported that impermeable covers reduce odor from manure ponds by 95% (Nicolai et al., 2004 and Bicudo et al., 2004). The value is typically not 100% because pond covers can be removed periodically for agitation and pump out of manure. A geosynthetic impermeable cover will prevent the release of volatile compounds and gases to the environment. There are two main cover designs.

Slurry Storage. The first mechanism is the prevention of evaporation of volatiles from the surface of the manure pond. The impermeable cover prevents the surrounding air from contacting the pond surface suppressing evaporation. The space underneath the cover becomes saturated with water vapor and other gases restricting the movement of volatiles and keeping odor causing gases in solution. Any gas that accumulates is drawn off and destroyed with a flare or other device. Often a slight vacuum is applied to the underside of the cover to keep the cover flat on the liquid surface (controlling head space). This type of system is often used in swine operations and gas destruction is metered for carbon credits in some countries. In swine operations an annual agitation and pump-out are common practices. Odor control is often compromised during this pump-out activity and covers are frequently damaged. Key factors in the design of this cover type are that the cover needs to move up and down with the manure level and must accommodate agitation and pump-out.

Biogas Collection. The second mechanism is to use an impermeable cover to create an anaerobic digester for the treatment of manure contaminated water. Typical of the dairy and beef industry this mechanism uses a solids separation step to keep the dissolved solids low (often less than 5%) and to recover bedding material. The waste water goes to a covered pond where significant biogas can be produced. The biogas can be collected for alternative energy use or flared. In this type of system the cover can often lift off the surface of the pond storing gas underneath the cover. The most successful covers are operated at a constant liquid level and are never opened for agitation or pump-out. In these digester systems all gases are contained and either destroyed or used. Any emissions that do occur are from the biogas use system and can include products of combustion such as oxides of nitrogen or sulfur. Recent designs in California are cleaning the biogas and selling it as utility gas which transfers the burning of the gas off the farm entirely. Once covered these ponds do not produce any discernable odor. Key factors in the design of this cover type are the efficient movement of biogas and the tension in the cover to prevent wind damage when lifted.

Applicability:

Current practice in geosynthetic covers is to fabricate the cover on-site using a specialized crew. This type of construction is applicable to large scale installations but is not economical for smaller facilities. Layfield's new prefabricated cover design requires less on-site expertise and can be installed economically on smaller installations. This new patent-pending design incorporates pockets in the cover that can hold floats or weights. These floats and weights are factory fabricated further reducing field installation requirements. Fabricated covers are made up to 2400 m^2 (about half an acre) in one piece and larger covers are welded together in the field. This new cover design would be applicable to ponds up to about 20,000 m^2 (5 acres). Larger covers would be fabricated on-site using a specialized crew.

Slurry Storage Covers are normally used in the swine industry for odor control but are applicable to any manure storage where the solids content is above 5%. These covers are used to control odors through the prevention of evaporation of volatiles and gases during the storage of the manure. The end use for the manure in these applications is land application which is typically done annually. The cover needs to accommodate pond level changes from empty at the beginning of the season to full just prior to agitation and pump out. Floats and weights in the cover are needed to control the slack that develops as the cover changes levels. The troughs formed by these floats and weights are used for rain removal on top of the cover (small pumps are used to remove the water). Layfield's new cover design used factory fabricated floats to create the rainwater and slack control systems. Although biogas handling is usually not the main purpose of a slurry storage cover some gas handling under the cover is required. Layfield's design includes a gas collection pipe around the perimeter. Previous slurry storage cover designs required that the covers be pulled back for agitation and pump-out. Layfield's design includes a large hatch that can be opened for agitation and pumping. The hatch allows the cover to be permanently installed reducing the chances for damage and leakage. Careful selection of agitation systems to protect these covers is recommended. Enclosed jet pumps are recommended over open propeller type pumps and air agitation systems are preferred over mechanical agitation. A modified design of the slurry storage cover is available for manure storage tanks; however, tank storage agitation and pumping issues have not been completely resolved yet.

Biogas Collection Covers are applicable to anaerobic digesters and water treatment systems with low solids contents (less than 5%). This type of system is typical of dairy or other facilities where there is effective solids separation prior to water treatment. This is also the system that would be applicable to industrial waste water treatment systems. The water level of these systems is constant and the covers are designed with no slack in the system. The cover is floated into place on a full pond and not removed for the design life of the cover. The small amount of slack in the cover is important to limit cover lifting under the pressure of biogas. The cover is weighted with a series of special weights to prevent wind damage of the lifted cover. Layfield's new cover design uses liquid filled weights that are prefabricated in the factory. These weights are filled after cover deployment and can be drained if the cover needs to be removed for maintenance in the future. In most locations these weights would be filled with water and would only exert tension once the cover starts to lift. Weight fluids with low freezing points can also be used to retain weight tube flexibility in cold temperatures. Additional sand-filled weight tubes are added after cover installation where factory fabricated pockets are not practical. Factory fabricated floats may also be included in these types of covers to enhance biogas movement to a perimeter collection pipe. Rainwater control is done by small pumps at the intersections of the cover weights. Adjustable safety valves that control the amount of cover lift are attached to the cover prior to deployment. These safety valves can be adjusted after installation to control the maximum amount of gas stored under the cover. The biogas produced by biogas collection covers is typically fed into a control system prior to use and uncontrolled odor and gas releases from these systems are rare.

Hybrid systems are being discussed where a biogas collection cover needs to accommodate significant changes in liquid levels over the year and/or periodic pump-out. If pond liquid level changes are required in a biogas collection cover then storage of biogas under the cover may not be practical. Alternative biogas storage systems such as gas bags may be needed in hybrid systems. Layfield's new cover design can incorporate both floats and weights into the same cover and that flexibility could be used to design a hybrid cover system.

Limitations:

The new Layfield prefabricated cover is designed for smaller ponds for odor control and biogas collection. The best pricing on these systems will be for ponds where the narrowest cover dimension is 300 ft or less. Long, narrow ponds are easiest to cover with this cover system; however all pond sizes are possible.

The current limitations in the use of impermeable cover technology are that pond liquid level changes (typical of agitation and pump-out) cannot easily be incorporated into a biogas collection cover. Biogas collection covers should have very little slack so that wind will not damage them if they lift off the pond. Slurry storage covers should be designed so that gases are drawn off to keep the cover from lifting.

In cold climates biogas production can be compromised when temperatures fall. Insulation panels are available that can be placed under a biogas cover to maintain liquid temperatures and to extend the season for the production of biogas. Insulation panels are available as an extra charge.

The liquid filled weight tubes in the biogas cover are designed so that they will not be damaged by freezing. In many locations in the US the surface of a manure pond will not freeze completely in the winter and water filled tubes are satisfactory. If weight tube freezing causes problems in a particular area then a non-freezing liquid can be used to fill the weight tubes. There are a number of liquid food byproducts that can be used for weight that will not freeze.

A floating cover will be locked in the ice when the surface of a pond freezes. For locations where an ice cover in excess of 6" forms adjustments to a slurry storage cover design may be required. Anything other than small changes in liquid levels when the cover is frozen in the ice could cause damage.

Layfield's prefabricated gas collection covers are made to order to fit a specific pond size. Orders must be placed with sufficient time to consult on the design, obtain materials, schedule fabrication, and arrange installation. Seasonal workloads will affect the time needed to fill these orders. Contacting Layfield early in the development of the project will prevent delays later.

Cost:

Cover costs have typically been estimated as construction projects with specialized installation staff. The new Layfield cover is prefabricated in the factory and delivered to site mostly assembled. Installation requires one or two skilled people to perform welding and direct the work. Freight costs may vary depending on the distance from a fabrication location; however, freight for these covers does not significantly increase the costs.

Typical cost for these covers is independent of whether it is a slurry storage cover or a biogas collection cover. The details of both covers are slightly different but the resulting end price is about the same. Cost of the cover would include the supply of the cover, the on-site welding, placement of floats or weights, installation, and filling of weight tubes. A gas collection pipe underneath the perimeter of the cover would be included. Anchor trench excavation and backfill are not included but an estimate of $2.50 to $3.00 per lineal foot is appropriate in most locations. The supply of equipment on site would be extra – typically a front-end loader would be available at most facilities and would be borrowed for the installation. Local labor would also be needed – typically 8 to 10 people for up to two days. Most projects will take two days to install but will require good weather for those two days (no precipitation and wind under 12 mph). Weather delays can incur standby charges. Other materials required to be supplied on site are a quantity of sand for making sandbags (wind safety) and a source of clean water to fill weight tubes (contaminated water is not suitable).

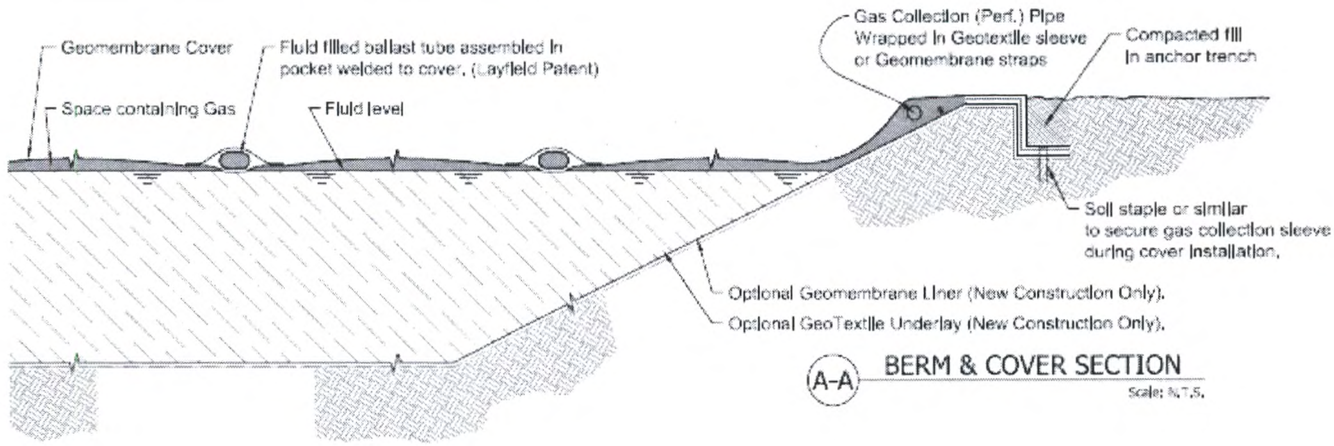
Cost for the supply and installation of Layfield's new slurry storage or biogas cover would be between $15.60 and $20.98 per square meter ($1.45 and $1.95 per square foot) of surface area depending on project specifics. The development of a standard size of pond requiring 5 or more identical covers would reduce the price. Alternative weight fluids (other than water) would be quoted extra. Hybrid cover systems would require a special quote and would be above this price range. Insulated panels are also extra if needed.

We recommend that you contact Layfield early in your project design phase to provide an accurate estimate of cover costs based on facility requirements.

Implementation:

The development of this new prefabricated cover was part of Layfield's ongoing development of covers for manure storage. Initial prefabricated covers were used for swine slurry storage. These covers were simple in design and were pulled back for agitation and pump-out. Damage to these covers led to significant design changes including the addition of floats and weights and the use of a stronger new material.

These changes were incorporated into a full scale design trial that was installed in the summer of 2006. The 4,000 m^2 pond cover (about an acre) was installed in a single day in a farm pond north of Edmonton Alberta Canada. This cover is used for ongoing trials with weights, floats, and rainwater removal systems.
The innovation prototyped in this new cover was a special sleeve that can hold either floats or weights. The arrangement of these sleeves and their preparation is the subject of a current US patent application.



Working from approved pond drawings a layout and estimate are prepared for a prefabricated cover. Details of the operation of the pond are discussed with the client and a slurry storage or biogas collection design is developed. Materials are ordered and the fabrication of the cover is scheduled. Fabrication can be completed well in advance of planned installation.

Prefabricated panels are shipped to arrive at site in time for planned installation. These panels can be shipped in advance and stored if required. Prior to installation the site is prepared. A laydown area is cleared next to the pond (typically on one end). Sand is delivered for sandbags and the anchor trench is excavated. Other site preparation may be completed such as the installation of specific gas piping but this is usually part of the installation planning and is unique to the project.

Skilled installers arrive at site and inspect the area. Local equipment and laborers stage materials, fill sand bags for wind safety, place gas collection piping, and rig pulling ropes for deployment of the cover. Once weather permits the cover materials are unrolled in the laydown area and welded together into a panel large enough to cover the pond.

A leading edge float is inserted into a pocket on the leading edge and pull ropes are attached. If floats are to be inserted into the prefabricated pockets then they are inserted during deployment. Weight tubes will usually be installed at the factory and will not need to be inserted during deployment. It takes about 15 minutes to insert a float into a cover pocket during deployment. The floats are wrapped in a sleeve that makes insertion easier and also controls where the floats end up in the final cover.

Slurry storage covers may be installed on full or partially full ponds. The required slack in the cover is measured and adjusted after it is pulled into place. The anchor trench is backfilled after the slack has been placed. In new construction the cover can be assembled in the bottom of the new pond. A special hatch is designed into the end of the pond normally with a permeable cover.

Biogas collection covers are only deployed over full ponds. The pond must be brought to operating level prior to floating in the cover. The cover is floated into place, the anchor trench backfilled, and then the weight tubes are filled with liquid.

Once installed and the anchor trench backfilled additional sand tubes are placed to complete the design of the cover. Biogas safety valves are adjusted as needed and the gas collection tube is connected to the gas collection system

Technology Summary:

Impermeable covers have been shown to reduce odors by 95%. This paper introduces a new, patent-pending, prefabricated cover that is economical for small and medium size manure containments. The cover is adaptable for both slurry storage (variable liquid level) and biogas collection (constant liquid level) applications. The cover costs between $15.60 and $20.98 per square meter ($1.45 and $1.95 per square foot) and installation is quick and requires minimal resources. The cover mitigates air emissions by either holding volatile gases in solution or by drawing off gases for use or destruction.

Additional Resources:

Layfield Web Site http://www.layfieldgroup.com (select Floating Covers)

Layfield's REVOC® BioGas Collection Covers
http://www.floatingcovers.net/index_product2.cfm?ID=geo&divID=3&applicationID=79&pass=product&productID=194&type=2&return=yes#194

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As published in the proceedings of:
MITIGATING AIR EMISSIONS FROM ANIMAL FEEDING OPERATIONS CONFERENCE
Iowa State University Extension
Iowa State University College of Agriculture and Life Sciences
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Negative Air Pressure Cover for Preventing Odor Emission from Earthen Manure Storage

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University of Manitoba[1], DGH Engineering Ltd.[2]

Species: Swine
Use Area: Manure storage
Technology Category: Cover
Air Mitigated Pollutants: Odor

Description:

Open earthen manure storage basins (EMSB) are the main source of odor from swine operations. Manure storage faculties are not only the most visible odor source on a farm, but odor from manure storage tends to be more persistent in the atmosphere in comparison with odor from barns. Covering manure storages is an effective way of minimizing odor emission. Synthetic plastic covers have been used and shown to be effective in reducing odor emission. In order to ensure the cover is robust enough to withstand wind forces however, the plastic covers become too heavy and expensive to be attractive to the livestock industry. DGH Engineering Ltd. in Manitoba, Canada has developed a unique technology that utilizes negative air pressure (NAP) to anchor lightweight plastic covers capable of withstanding high wind forces. This patented technology is available from Encon Technologies Inc., Manitoba, Canada. The NAP system has been evaluated on several farms. A comparison of odor emissions between a NAP covered and an open EMSB was conducted on two 3000-sow farrowing facilities which were almost identical in design and management. The average emission rate from the NAP covered manure storage was 0.3 OU $s^{-1}m^{-2}$, which is negligible in comparison with the rate from the open manure storage (20.3 OU s^{-1} m^{-2}). Additional benefits of the NAP cover system include the retention of manure nitrogen, thus increasing the fertilizer value of manure; isolating precipitation from the manure, thereby increasing storage volume; and reducing greenhouse gas emissions.

Mitigation Mechanism:

Odor emission from EMSB occurs in three main steps: production of odorous compounds due to anaerobic degradation of organic matter in manure, transport of odorous compounds to the manure surface (bubbling and diffusion); and release of odorous compounds from the manure surface to the atmosphere. A cover forms a physical barrier between the manure surface and the atmosphere to prevent odorous compounds from being released into the atmosphere, thus eliminating or reducing odor emission. An impermeable cover could theoretically eliminate odour emission during storage, although trapped odorous gases may still be released during agitation and land application.

A challenge to using plastic covers on EMSB is to prevent the covers from being damaged by wind forces. The use of *heavy* plastic would allow the cover to withstand wind forces, but the cost becomes unattractive to livestock producers. Heavy synthetic covers require significant foundations that also substantially increase cost. The uniqueness of the NAP cover system is using *lightweight* plastic (e.g., 20 mil reinforced polyethylene) and an air pumping system to create negative pressure to hold the cover down to the manure surface to resist wind forces (fig. 1).

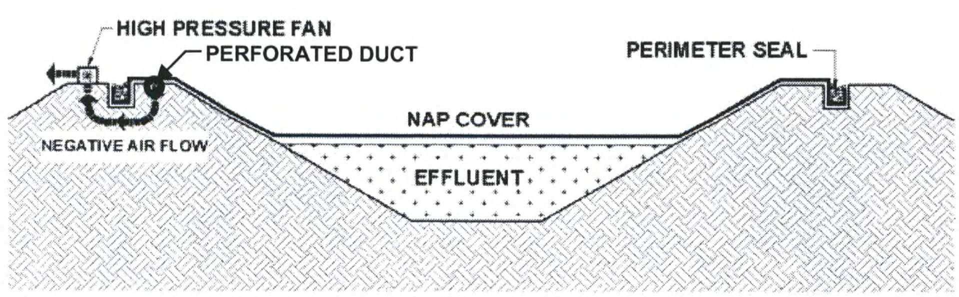

Figure 1. Illustration of negative air pressure cover for earthen manure storage basin (ENCON 2008)

Negative air pressure is created by using small (high pressure, low flow rate) exhaust fans that are connected to the perforated duct placed beneath the cover along the perimeter (fig. 1). Typically, the fans develop a negative static pressure of approximately 62 to 374 Pa (1/4 to 1.5 in of water) under the cover. The impermeable plastic cover virtually eliminates the transfer of odorous gases from the manure surface to the atmosphere. The fans that create the negative air pressure may, however, release a small amount of odorous air to the atmosphere. The air flow rate of the exhaust fans is very low (about 50 - 70 L/s per fan) and most of this air is leakage of fresh air that occurs at the perimeter seal. The net result is that odor emission is insignificant.

Applicability:

The NAP cover system is effective in reducing odor emission from earthen manure storage basins for swine operations (fig. 2), as well as other types of liquid waste storage facilities. Small and Danesh (1999) performed a subjective assessment of odor around a NAP covered swine manure storage basin. They reported that odor was not detectable during fall, winter and early spring, and a slight odor was detectable downwind and at close proximity to the fan outlets during the summer months. Zhang et al. (2007) conducted a study to compare odour emissions between an open and a NAP covered EMSB for two swine farrowing operations of 3,000-sows which were almost identical in design and management. The NAP covered EMSB had two cells (61 x 51 m primary cell and 61 x 155 m secondary cell). Eight exhaust fans that were used to create negative pressure for holding down the covers (two in the primary cell and 6 in the secondary cell) drew 0.6 m^3/s air (about 160 cfm per fan), resulting in an odor emission rate of 3.8×10^3 OU/s, which is about 2% of that from the open EMSB in comparison (1.7×10^5 OU/s). When the emission rate was expressed as per m^2 of the manure surface, the weighted average rate of the two cells of the NAP covered EMSB was 0.3 OU $s^{-1}m^{-2}$, which is negligible in comparison with the rate from the open EMSB (20.3 OU s^{-1} m^{-2}). Furthermore, the open EMSB contributed 57% to the total odor emission (building plus manure storage), whereas, the NAP covered EMSB contributed only 2%.

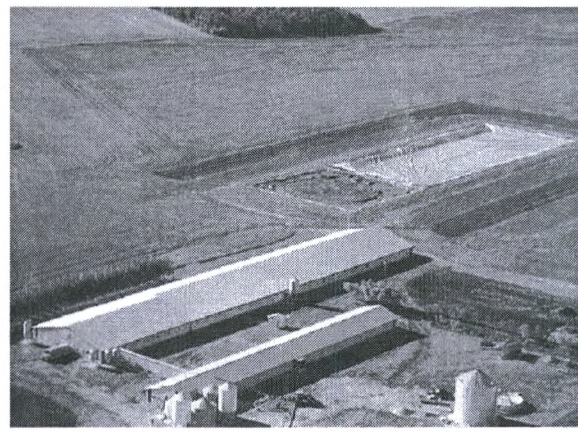

Figure 2. Installed negative air pressure cover system in a swine farrow-to-finish operation

Zhou et al. (2005) conducted field measurements to assess the impact of the NAP cover on downwind odor. Fifteen human odor sniffers were trained to use an 8-point ASTM Odour Intensity Reference Scale (ASTM 1999) to quantify the field odor intensity within a 1-km radius of two 3,000-sow farrowing facilities, one with a NAP EMSB and the other one with an open EMSB. Based on the data from Zhou et al. (2005), Gu et al. (2006) developed predictive equations for downwind odor intensity for the two facilities (fig. 2). Downwind odor intensity from the facility with the NAP EMSB was about 1.5 levels lower than that with the open EMSB at 100 m and the difference was 0.5 intensity levels at 1 km. If the intensity level 3, which describes an odor intensity of *little annoyance*, is used to define the odor annoyance free distance (OAFD) (I = 3, OAFD = D in predictive equations), the NAP cover resulted in an OAFD of 667 m, whereas the open EMSB 926 m. This implies that the NAP cover could reduce the setback distance by 28%.

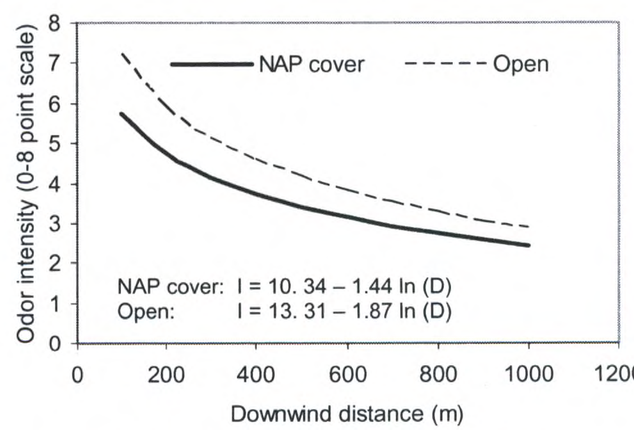

Figure 3. Odor intensity downwind from two 3000-sow farrowing operations. I= odor intensity (0-8 scale); D = downwind distance (m).

The cover can also be utilized to capture methane which is a greenhouse gas (GHG). Livestock producers utilizing this technology could potentially sell carbon credits. The methane released from the manure forms large bubbles under the cover. Typically, the large bubbles slowly move with the wind toward the side of the storage, where they are then evacuated by the fan and duct system. This "burping" will normally occur once or twice per day in warm weather (May to September) when the anaerobic bacteria are most active. Since the methane is released from a limited number of fan outlets, it can be easily flared off.

Limitations:

The solids in livestock manure require agitation to maintain the solid particles in suspension so that they will be removed with the liquid during pump-out. Traditional agitation involves the use of large tractor powered pumps that are backed into the storage and operated continuously to agitate the manure, while a second pump is simultaneously operated to remove the manure from the storage. This procedure requires that the cover be removed from the storage cells that contain manure solids.

Removing and replacing the cover annually or semi-annually for pump-out increases the wear on the cover and adds labor and time to the pump-out operation. To solve this problem, DGH Engineering has designed an air assisted agitation system that does not require removal of the cover. A grid of small air lines injects air into the bottom of the storage through diffusers located in a one metre grid (fig. 4). A blower (operating at a pressure of approximately 100 kPa) provides the air for agitation. Since this system agitates the complete storage, agitation and solid removal is improved over traditional pump systems and the risk of damage to clay liners is eliminated. The cost of installing and operating the air agitation system is comparable to conventional systems.

To assist with the filling and emptying of the manure storage, separate concrete wet wells are often utilized. Concrete ramps normally installed for conventional pumps can be eliminated with the NAP cover and air agitation system.

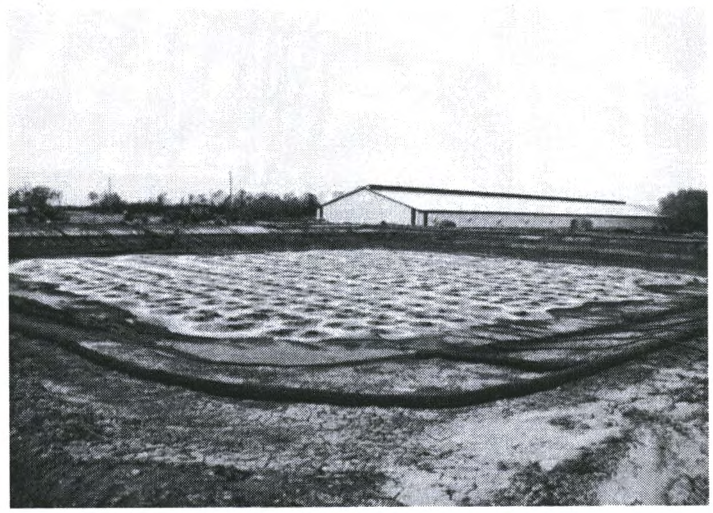

Figure 4. Air assisted agitation system in operation

Cost:

The capital cost of the cover varies with the size of the storage; whether the EMSB contains one, two or three cells; the complexity of the installation (existing sites may have various appurtenances) and the location. Typical costs vary from \$10.00 to \$15.00 per m², installed.

The annual cost per pig marketed for typical 5,000 and 10,000 head swine finisher operations is estimated to be \$1.40 and \$1.13, respectively, per pig marketed. The following assumptions were used in determining these costs:

Lifespan of cover:	10 years
Interest rate:	8 percent
Maintenance and Repairs:	3 percent of capital cost
Energy cost:	6 cents per kilowatt-hour
Barn efficiency:	2.8 pigs marketed per pig place

The fans used to maintain the negative pressure are ¼ kilowatt centrifugal blowers that run continuously. A large EMSB typically utilizes four to six fans.

Offsetting the cost of the cover is the value of the nitrogen retained by the cover. A 5,000 head swine finisher operation will excrete approximately 50,000 kg of nitrogen annually. Nitrogen losses from a NAP covered EMSB are negligible. Losses from uncovered storages vary widely but are reported to vary between 30 to 50 percent (Agricultural Guidelines Development Committee 1998). Assuming a loss of five percent for a NAP covered EMSB and 40 percent for an open EMSB, approximately \$20,000.00 of nitrogen can be retained annually, based on a nitrogen cost of \$1.10 per kilogram. The nitrogen saved is approximately equivalent to the cost of the cover.

In comparison with permeable EMSB covers, such as straw, an additional economic advantage of the NAP cover is the potential gain in storage capacity due to the isolation of precipitation. With a NAP cover, precipitation remains on top of the cover as clean, uncontaminated water until it is pumped off. In a large portion of the Great Plains region of North America, evaporation is approximately equal to precipitation, therefore a NAP cover has no advantage compared to an uncovered EMSB. However, with a straw cover, all precipitation enters the storage through the porous straw. Evaporation, however, is negligible through the heavy mat of straw. In the example of the 5,000 head finisher barn, approximately 2500 m³ of storage capacity can be gained where the annual precipitation excluded is 300 mm. EMSB construction costs vary widely but a value of \$10.00 per m³ is typical. In the eastern maritime regions of North America, annual precipitation can exceed 1000 mm; the value of the storage volume saved will nearly pay for the cover in these areas.

Implementation:

The NAP technology is patented in both Canada and the United States. It is available exclusively through Encon Technologies Inc., St. Andrews, Manitoba, Canada. Encon only supplies installed covers therefore all design and construction details are proprietary.

In general, the cover material varies from 0.4 to 0.7 mm and is a low density polyethylene. The cover is either permanently anchored in an earthen trench, which is typical for second cells that do not contain manure solids requiring agitation; or it is anchored with sand bags in trenches for removal of the cover. The cover material is treated for ultraviolet light and has a life span of approximately 10 years or greater.

Technology Summary:

Impermeable synthetic covers block the transfer of odorous compounds from the manure surface to the atmosphere, thus eliminating or reducing odor emission from earthen manure storage basins. DGH Engineering Ltd. in Manitoba, Canada, has developed a unique technology that utilizes negative air pressure (NAP) to anchor lightweight plastic covers to ensure the cover is robust enough to withstand wind forces. The NAP cover system uses small exhaust fans to create a negative pressure between the synthetic cover and the manure surface in order to hold down the cover, thus preventing wind damages to the cover. Odor emission from the NAP cover is negligible. The capital cost of a NAP system from Encon Technologies Inc., Manitoba, Canada is approximately $10 to $15 per square metre, with a service life of ten years or more. The value of the nitrogen retained by the cover is approximately equivalent to the cost of the cover. Other benefits can include additional storage volume gained from eliminating precipitation and the reduction of GHG emissions.

Additional Resources:

Additional information on the NAP cover system can be obtained from www.enconcovers.com or by contacting Doug Small of DGH Engineering Ltd., (204) 334-8846.

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As published in the proceedings of:
MITIGATING AIR EMISSIONS FROM ANIMAL FEEDING OPERATIONS CONFERENCE
Iowa State University Extension
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Manure Storage-Treatment

RAPP Technology for Control of Gas and Odor from Swine Manure Pits

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Purdue University[1], Valparaiso University[2], Juergens Produce & Feed Company [3]

Species: Swine
Use Area: Manure Storage, Manure Treatment
Technology Category: Chemical Amendment
Air Mitigated Pollutants: Odor, Ammonia, Carbon Dioxide, Sulfur Dioxide

Description:

This paper presents the results of a laboratory study of a new manure treatment method, patented by Rapp Technology, to reduce gas and odor emissions from swine manure. The study followed the National Pork Producers Council (NPPC) protocol previously used in testing 35 commercially available pit additives in 2000. Six manure reactors, three treated and three controls, were used to simulate the deep manure pit and were tested side by side for 49 days. Test results showed that, relative to the controls, emissions of ammonia, carbon dioxide, and sulfur dioxide from the treated reactors were reduced by 93% ($P<0.05$), 83% ($P<0.05$), and 84% ($P<0.05$), respectively. Emissions of hydrogen sulfide were 39% less than the controls, but the difference was not statistically significant ($P>0.05$). The odor concentration was significantly reduced ($P<0.05$) from 2772±184 to 1857±420 OU/m^3 (OU = odor unit) with the air inlet at 568±71 OU/m^3 in one set of valid samples. In addition to mitigating air emissions, the technology also caused a significant increase in total and ammonium nitrogen in the treated manure relative to untreated manure accompanied by a significant decrease in total phosphorous.

In the previous test of 35 pit additives by the NPPC, the best reductions of ammonia and hydrogen sulfide emissions were 15% ($P>0.05$) and 47% ($P>0.05$), respectively,. None of the 35 pit additives study showed a statistically significant reduction in odor concentration (Heber *et al.*, 2001). Thus, the Rapp Technology presented in this paper was more effective for air pollution abatement.

Mitigation Mechanism:

The Rapp pit treatment technology consists of two component parts. The first part is an oil cover floating on the surface of the manure slurry to slow the rate of volatilization of the offensive molecules. The oil cover allows excrement to drop through it. The second component part is an alkaline solution, which is injected beneath the cover. This solution contains NH_3 (a base) that neutralizes the volatile fatty acids and phenols in the slurry to their ammonium salts. Such salts are more prone to stay in the aqueous slurry because they are more water-soluble and less volatile than the original acids. Keeping these acids out of the air decreases the stench. Moreover, there is an added benefit accompanying neutralization of the slurry. In anaerobic environments, certain anaerobes (acetogens) chemically change the long-chain fatty acids (which are non-volatile and insoluble in water) found in manure solids into shorter-chain fatty acids (which are more volatile and water soluble) such as those on the list of compounds most responsible for the offensive odor of manure (Zahn *et al.*, 2001). This chain length reduction generates an odor, which can persist if the digestion process stops at this stage due to excessive acidity destroying other anaerobes (methanogens), which would otherwise complete the digestion process. The complete digestion process converts the volatile fatty acids into odorless gaseous compounds (carbon dioxide and methane). Thus, adding an alkaline solution to the slurry neutralizes the volatile fatty acids keeps them in solution, and promotes their removal through complete digestion.

Applicability:

This technology was designed for deep manure pits. During the laboratory study to simulate the deep pit, liquid swine manure collected from a finishing operation was tested at Purdue University in manure reactors, made from 38-cm diameter, 122-cm tall PVC pipes that had removable sealing caps (Figure 1). Following initial filling with 75 L of manure, to a depth of 66 cm, swine manure was added weekly for five weeks starting on day 6. Each reactor received 5.8 L of liquid swine manure, which was equivalent to 5 cm manure in each reactor during the weekly addition. The reactors were ventilated with clean room air of 7 L/m during the test. Concentrations of gases, including ammonia, hydrogen sulfide, sulfur dioxide, and carbon dioxide in the inlet air and reactor exhaust air were measured with gas analyzers continuously for 10 min each reactor. The inlet air and exhaust air were sampled twice for odor measurement with a trained odor panel using a dynamic olfactometer.

The oil cover used in this study was provided commercially (Custom Formulating & Blending, Bristol, IN). The oil was a petroleum product (325 SSU) that is considered agriculture oil, and can be used in crop production applications. The addition of the oil to the three treated reactors occurred only on day 0. Each reactor received 1.5 L of oil, or a 1.3 cm thick oil cover, which was poured onto the surface of the manure (Figure 2). Three other untreated reactors were used as controls.

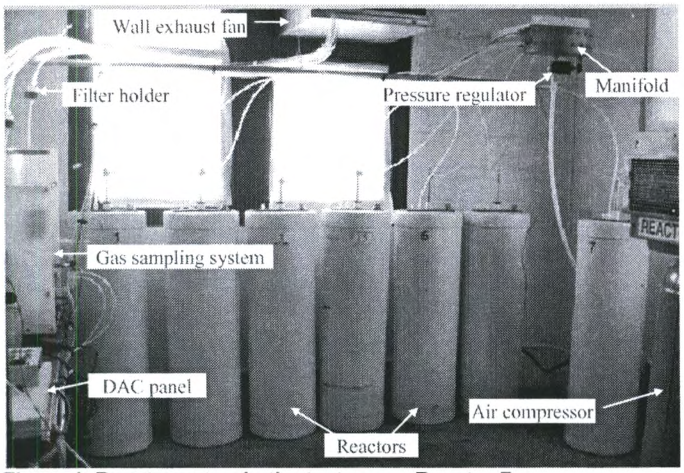

Figure 1. Reactor setup in the test room. Reactor 7 was a spare.

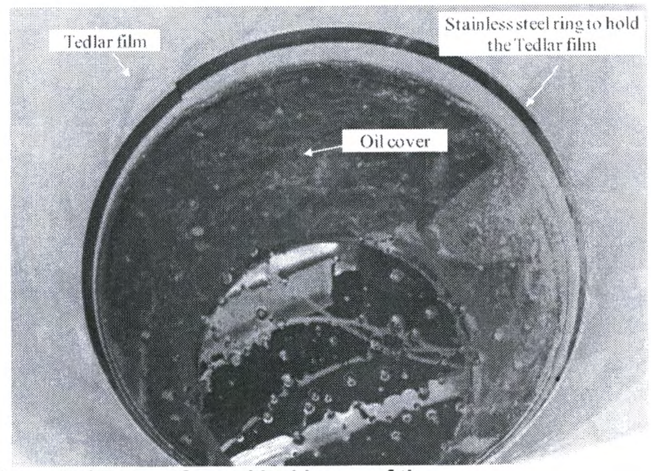

Figure 2. Oil cover formed inside one of the treated reactors on day 0.

The neutralizer used in this study was also provided by Custom Formulating & Blending, Inc, Bristol, IN, and formulated by Rapp Technologies, Athens, Illinois. The neutralizer was added to the bottom of the reactor through the pH probe and neutralizer addition assembly, using a 30-mL syringe. A total of six neutralizer additions occurred over the duration of the study, on days 0, 2, 6, 37, 44, and 48. The initial addition of neutralizer to each of the treated reactors on day 0 was 288 mL. On days 2, 6 and 37, each reactor received 144, 60 and 30 mL of neutralizer, respectively. The fourth addition occurred on day 44 with 60, 30, and 0 mL of neutralizer to reactors 2, 4, and 6, respectively. The final neutralizer of 30 mL was added on day 48 to each of the treated reactors. The air supply was shut off during this procedure, and all ports were open to allow the neutralizer to flow into the manure.

The study results showed that the emission rates of ammonia and carbon dioxide from the treated reactors were reduced by 93% ($P<0.05$) and 83% ($P<0.05$) compared with control reactors, respectively. These reduction rates were much higher than any previous tests of manure additives reported in the literature. The treatments also reduced sulfur dioxide emissions by 84% ($P<0.05$). These results showed that the oil cover was very effective in reducing gas emissions from simulated deep manure pits. The treated reactors also showed 39% lower hydrogen sulfide emission rates than the controls. However, the reduction was not statistically significant, due to large variations caused by hydrogen sulfide burst releases (Ni *et al.*, 2000). Two valid odor samples at the end of the test showed reduction of odor concentration for the treated reactors. The odor concentration for the last sampling, which also had double size sample numbers, was statistically significant ($P<0.05$). The odor concentration for the control reactors, treated reactors, and air inlet were 2772±184, 1857±420, and 568±71 OU/m^3, respectively.

Figure 3 presents daily mean ammonia emission rates from the two groups of reactors. Because of the constant air supply to the reactors, the daily mean gas concentration patterns were similar to the emission rate patterns. Figure 4 presents daily means of carbon dioxide emissions from the two reactor groups. Although all the reactors experienced a general increase in emission rates from the start to the end of the test, the changes were relatively small before the third weekly manure addition on day 27, when manure with high dry matter (DM) content was introduced into the reactors. The variations of carbon dioxide emissions within the groups were less than those of hydrogen sulfide and sulfur dioxide. Figures 5 and 6 plot the daily mean emission rates of hydrogen sulfide and sulfur dioxide from the two groups of reactors from day 14 to the end of the test. During this period, hydrogen sulfide emissions from the control and treated reactors demonstrated a strong fluctuation pattern. In Figures 3 to 6, arrows indicate manure addition days and diamond arrows indicate neutralizer addition days.

Table 1 lists manure analysis results at the end of the study before and after thorough agitation of the manure. The treated reactors had higher TKN ($P<0.05$), NH_4-N ($P<0.05$), and lower P ($P<0.05$) as compared with the control reactors. Both the control and treated reactor samples had higher DM after agitation as compared with those before agitation. The agitation of the treated reactors caused significant increases ($P<0.05$) in TKN and NH_4-N, while there was only a numerical increase ($P>0.05$) in TKN and NH_4-N for the control reactors after agitation. An apparent reason for the difference before and after the agitation was that the manure with higher DM settled at the bottom of the reactor before and was more evenly distributed following the agitation. Therefore, the characteristics of the agitated manure samples better represented the actual mean values.

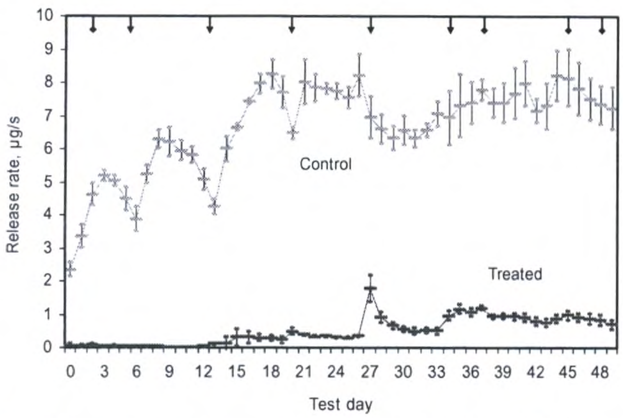

Figure 3. Daily mean ammonia emission rates and 95% confidence intervals from the two reactor groups.

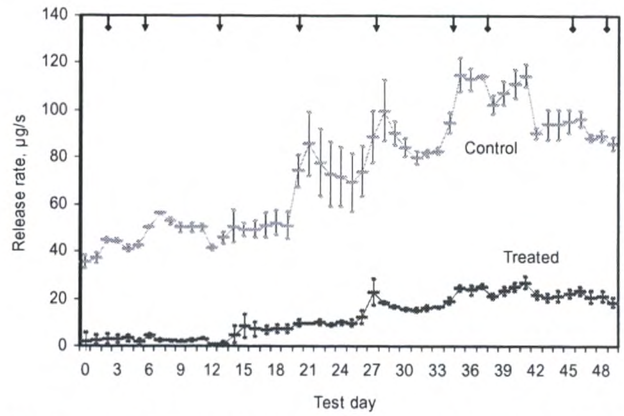

Figure 4. Daily mean carbon dioxide emission rates and 95% confidence intervals from the two reactor groups.

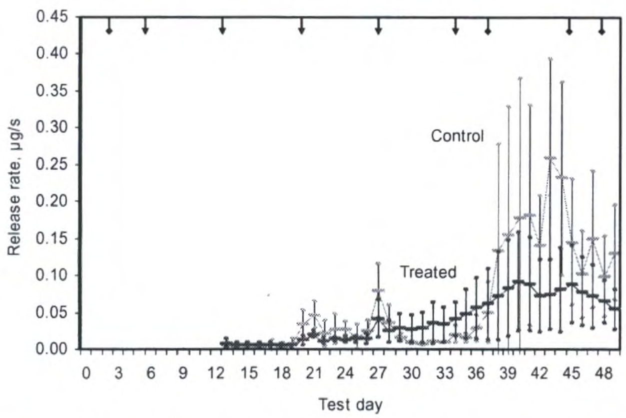

Figure 5. Daily mean hydrogen sulfide emission rates and 95% confidence intervals from the two reactor groups.

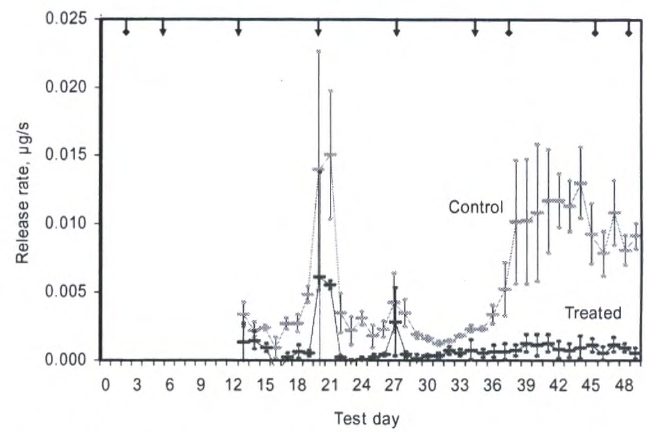

Figure 6. Daily mean sulfur dioxide emission rates and 95% confidence intervals from the two reactor groups.

Table 1. Characteristics of reactor manure on day 49 (mean 95%±confidence interval)

	Before Agitation		After Agitation	
	Control	Treated	Control	Treated
Sample n	3	3	3	3
DM, %	0.72±0.02	0.73±0.05	0.87±0.02	0.81±0.02
TKN, mg/L	1852±127	2207±67	2010±64	2396±30
NH_4-N, mg/L	1774±114	2115±153	1902±121	2286±56
P, mg/L	132±3	106±7	202±8	184±3
pH	8.2±0.2	8.0±0.02	8.1±0.07	8.0±0.01

Limitations:

The oil cover floats on top of the liquid manure and creates a barrier for reducing gas and odor emissions. It works well for accumulated liquid manure such as the manure in pits. It is not suitable for applying on the manure on the barn floors. The effect of neutralizer on emission reduction could not be differentiated from the effect of oil cover in the lab test. Future high quality field studies are needed to optimize the application method, including the application of neutralizer, and to achieve maximum reduction with minimum costs.

Cost:

During the lab test, the oil and the neutralizer (both provided by Custom Formulating & Blending, Bristol, IN) cost $1.13 and $ 0.67 per reactor, respectively. According to Juergens Environmental Control (Carroll, Iowa) for field application of the neutralizer, the fixed cost of the system for 1000 to 8000-pig finishing operations averages $2.50 - $5.00 per pig per 3 year term (shipping and labor not included). The annualized cost of neutralizer operating averages $0.01 per pig per day.

Implementation:

This technology is a combination of manure coverage and manure amendment or additive. Because of using oil as the liquid barrier on top of manure, the cover allows manure to drop through the cover and is effective in reducing gaseous compounds from releasing from manure. The implementation of the oil cover is simple and does not require special equipment. Oil is biodegradable and easy to obtain.

According to Juergens Environmental Control (Carroll, Iowa), the implementation of neutralizer needs special equipment. The blended neutralizer solution with a proprietary formula is stored in a 5500-gallon poly storage tank near an 8 ft x 8 ft x 8 ft utility shed. The neutralizer solution tank is operated by a computer in the utility shed. PVC piping is plumbed from the storage tank to the main manifold located outside of the barn or manure storage station. The manifold has injectors placed at uniformly distributed areas in the manure pit. The computer is programmed to inject the solution six times a day for two seconds, pumping 1.34 gallons into the pit each time. Daily usage is subject to barn size.

Technology Summary:

This gas and odor reduction technology consists of (1) an oil cover that is floating on the surface of the manure slurry to slow the rate of volatilization of the odorous molecules. The oil cover allows excrement to drop through with only a brief disturbance of the cover, (2) an alkaline solution, which is injected beneath the oil to alter the chemical reaction in the manure. The laboratory study demonstrated significant reduction of ammonia, carbon dioxide, sulfur dioxide, and odor from the treated reactors. Compared with previously tested commercial manure additives, this technology is more effective in mitigating gas and odor emissions from simulated deep manure pits.

Acknowledgments:

The laboratory study was funded by USDA (Grant Number 2005-33610-15547) and Rapp Technologies. John Ray of Custom Formulating & Blending provided the neutralizer for the lab test. Peter Juergens of Juergens Environmental Control provided information about the neutralizer in field application.

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As published in the proceedings of:
MITIGATING AIR EMISSIONS FROM ANIMAL FEEDING OPERATIONS CONFERENCE
Iowa State University Extension
Iowa State University College of Agriculture and Life Sciences
Conference Proceedings
Sponsored by:
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U.S. Pork Center of Excellence

The Use of Anaerobic Digestion Systems to Mitigate Air Emissions from U.S. Livestock Production Facilities

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USDA Natural Resources Conservation Service[1], Iowa State University[2]

Species: Dairy, Swine, Poultry, Beef
Use Area: Manure Treatment
Technology Category: Anaerobic Digestion
Air Mitigated Pollutants: Odor, Methane, Hydrogen Sulfide

Description:

Liquid manure stored in open tanks, pits, ponds or lagoons will generate and release methane, hydrogen sulfide, and odor emissions. Anaerobic digestion (AD) systems reduce these emissions by generating and capturing biogas (which contains methane and hydrogen sulfide) as well as odor and ammonia that would normally be released to the atmosphere form an uncovered manure storage system. The methane, odor and trace amounts of other gases generated from the digested manure are collected as biogas, and the captured biogas can be combusted to produce heat or electrical power. Anaerobic digestion provides multiple environmental benefits including:

- Odor reduction
- Greenhouse gas emission reduction
- Production of a renewable energy source (biogas)

The biogas production efficiency of an anaerobic digestion system varies based upon digester type and design, manure type and amount, bedding material, and dilution water. Theoretical biogas production calculated for dairy, beef, swine and poultry is 1.9, 0.4, 0.2, 0.01m^3 of biogas/animal/day respectively (USDA NRCS, 2007). These values assume a 30% digester efficiency for dairy and beef manures, a 60% conversion efficiency for swine manure and a 70% conversion efficiency for poultry manure. Anaerobic digester system cost is variable dependent upon digester type and farm-specific conditions. Based on an analysis of 38 AD systems in the USDA NRCS Technical Note 1; *An Analysis of Energy Production Costs from Anaerobic Digestion Systems on U.S. Livestock Production Facilities*, published in 2007, one-third (1/3) of the system capital costs are associated electrical generation equipment. This analysis also suggests that it can be difficult for an anaerobic digestion system to provide any rate of return if electrical power is produced and sold back to the grid at wholesale power rates of around 3 cents per kilowatt hour. This same study concluded however that based on an analysis of 38 AD systems in the US, that an AD system appears to be economically feasible without subsidization when the biogas produced can be utilized for on-site heating without excessive gas cleaning costs.

Mitigation Mechanism:

For certain livestock operations, large amounts of stored manure result in odor that can create a nuisance for neighbors and greenhouse gas emissions that contribute to global warming. Odor, as well as methane, a greenhouse gas twenty-one times more effective than carbon dioxide at trapping heat in the atmosphere, forms under anaerobic conditions when manure is stored. Anaerobic digesters collect gases generated by manure during the anaerobic digestion process and route the odor and other trace gases along with the biogas to be combusted. The biogas and other collected gases are either flared or combusted as fuel in either a boiler, reciprocating internal combustion engine or a micro-turbine. Essentially, the system produces bioenergy from manure by generating and capturing methane produced by the digestion process. Manure is fed into the digester either by gravity flow or pumped from a collection sump into the digester. The manure undergoes digestion in a closed chamber for a hydraulic retention time period typically ranging from 20 - 60 days depending on the type of digestion system used. During this time bacteria break long-chain compounds into shorter chain compounds through hydrolysis, and these shorter chain compounds are in turn converted to volatile fatty acids during fermentation and finally the volatile fatty acids are converted to methane by methanogenic bacteria. The biogas collected from the top of the digester is flared or used for power. The digested effluent is discharged and used as a crop nutrient source, since the anaerobic digestion process does not remove manure nutrients. Following anaerobic digestion, the effluent will remain relatively odor free. The use of a manure anaerobic digestion system will reduce odor emissions from both the manure storage and land application process.

Applicability:

Anaerobic digesters have traditionally been utilized with liquid manure slurries. A variety of system types are available that are suited for different manure types and thus different animal species and production systems. Digesters have a better chance of providing an economic return if they combine income from various system outputs including utilization of the biogas, digested solids, effluent, and carbon credits.

The following types of anaerobic digesters have been demonstrated to work with animal manures to date.

Anaerobic sequencing batch reactor (ASBR) – An anaerobic digester configuration that is operated in a four-step batch mode. These steps are: 1) fill, 2) react, 3) settle, and 4) decant.

Continually stirred tank reactor (CSTR) - An anaerobic digester configuration where the system is continuously mixed and the manure in the digester is uniformly distributed. This digester type is also known as a Complete Mix system.

Covered anaerobic lagoon - Earthen structures, that may or may not include heat addition, designed to collect biogas produced from stored animal manures. These systems may use full or partial covers. A partial cover allows for biogas collection from the majority of the lagoon surface area while maintaining a simple system to allow collected rainwater to be drained from the covered area

Fixed-film digester - An anaerobic digester configuration where anaerobic microbes (biomass) are grown on a fixed structure within the digester. This digester configuration has excellent biomass retention and can therefore be operated at low hydraulic retention times. Manure contacts biomass attached to a structural surface in the reactor when it flows through the reactor. These systems are also known as Anaerobic Filters and may be designed to operate in either an upflow or down flow mode.

Induced blanket reactor (IBR) - An anaerobic digester contact process that uses a layer (called a blanket) of anaerobic biomass to digest manure as it moves through the digester.

Mixed digester - An anaerobic digester configuration where mixing occurs, but where the system is not continuously mixed as in a Complete Mix (or CSTR) system.

Plug-flow digester - A manure anaerobic digester configuration that typically uses a concrete horizontal tank with a flexible gas collection cover. Manure is pumped into one end of the digester and is displaced down the digester where it exits at the far end. A high solids manure is required to achieve plug-flow (no mixing) conditions within the digester. Plug-flow systems are commonly used with scrape collected dairy manures.

Upflow anaerobic sludge blanket digesters (UASB) - An anaerobic digester design that passes influent through a granulated sludge bed. This bed is composed of anaerobic micro-organisms (biomass) that digest the substrate as it passes through the bed.

System types that have been successfully integrated on multiple livestock operations to date include covered anaerobic lagoons, plug-flow digesters, and continually stirred tank reactors (mixed digesters).

Limitations:

Anaerobic manure digesters have a high capital cost when compared to tradition manure storage systems. Given the capital cost and the wholesale electricity rate usually received for excess power produced by a manure digester used to generate electrical power, it may not be possible to receive an economic return from an anaerobic digester based on power sales alone.

Methane, a colorless and odorless gas, is flammable. When exposed to air, biogas can be highly explosive depending on the methane concentration of the biogas. The AD system should be checked periodically for leaks. Safety precautions should be taken including the use of adequate flame traps and pressure reducers on biogas delivery lines.

Historically a large percentage of manure digesters installed in the US have not remained operational. In the past, poor system design, improper system installation, and unsatisfactory system management have been identified as reasons for the high percentage of manure digesters that are no longer operational (Lusk, 1998). A farm considering the installation of an anaerobic digestion system should be aware of the substantial capital costs, management and technical expertise needed to operate an AD system, and potential safety issues with handling flammable biogas (Jones, Nye, and Dale 1980). If a farm intends to sell the power generated to a utility provider, an analysis to examine the economic feasibility of such a venture should be undertaken.

Cost:

An economic analysis of 38 manure anaerobic digestion system installations is provided in USDA NRCS, 2007. The analysis is based on cost data available for specific anaerobic digestion systems that had been installed in the US over the last decade. For the 38 systems included in the analysis the capital cost adjusted to 2006 dollars for a covered lagoon anaerobic digestion system ranged from $88,000 to $162,000, and for plug flow anaerobic digestion systems cost ranged from $69,000- $603,000. The majority of the systems included in the analysis (19 of 38) were dairy plug flow anaerobic digestion systems. The average per head cost for the dairy plug flow systems was $543 per cow in 2006 dollars. These costs do not include an estimate for operation and maintenance costs, which was calculated as ranging from approximately 2-7% of the total capitol costs of the digester and generator set. Furthermore, the analysis concludes that approximately 36 percent of the total capital cost is associated with electrical generation equipment. Initial capital costs of electrical generation equipment ranged from $114,000 to $326,000 for the 38 case studies reviewed. The majority of anaerobic digestion system operation and maintenance (O&M) costs are associated with the electrical generation equipment (Kramer 2002). More information concerning electricity and biogas production costs for digester type by species is provided in USDA NRCS, 2007.

Implementation:

The installation of a manure anaerobic digestion system on a U.S. farm typically requires a significant capital expenditure. As of this writing (2008) manure anaerobic systems do not appear to be economically feasible for power production alone. The return from electrical power generated from biogas combustion will typically not provide enough revenue to provide a positive return on the capital investment. When the total benefits of an anaerobic digestion system, such as odor control, carbon credit sales, power and or heat generation, are combined however anaerobic digestion systems can provide a positive return for some farms.

After implementation, data to record and measure the performance of the AD system as instructed in *A Protocol for Quantifying and Reporting the Performance of Anaerobic Digestion Systems for Livestock Manures* (Martin, 2007) will lead to a better understanding of the long-term performance of anaerobic digestion systems.

Technology Summary:

Manure anaerobic digestion systems provide excellent odor control from manure storage and land application areas when manure is digested prior to these activities. In addition to odor control, anaerobic digesters also reduce greenhouse gas emissions when compared to conventional uncovered manure storage. The digestion process produces biogas which contains approximately 65% methane as biogas, and the captured biogas can bee combusted to produce heat or electrical power. Anaerobic digesters do not reduce nutrients however, so the same land requirement for nutrient management planning will remain after the installation of an anaerobic digester.

The installation of a manure anaerobic digestion system on a U.S. farm typically requires a significant capital expenditure and as of this writing (2008) manure anaerobic systems do not appear to be economically feasible for electrical power production alone. When the total benefits (odor control, carbon credit sales, power and or heat generation) of an anaerobic digestion system are considered in combination however, anaerobic digestion systems can provide a positive economic return for some farms.

Additional Resources:

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As published in the proceedings of:
MITIGATING AIR EMISSIONS FROM ANIMAL FEEDING OPERATIONS CONFERENCE
Iowa State University Extension
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U.S. Pork Center of Excellence

A Surface Aeration Unit for Odor Control from Liquid Swine Manure Storage Facilities

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University of Minnesota[1], Texas A&M University[2]

Species: Swine, Dairy, and Poultry
Use Area: Manure Storage
Technology Category: Aeration
Air Mitigated Pollutants: Odor

Description:

Odors generated from anaerobic lagoons have been a long-term issue that has been studied for years but without effective techniques in place to deal with it. The failure in controlling odors emitted from such manure storage structures has caused numerous lawsuits and soured the relationship between animal farmers and their neighboring residents. With the mounting pressures from the public and regulatory agencies, the sustainability and productivity of animal producers using lagoons for manure storage will be jeopardized and social ties strained if acceptable levels of odor reduction are not achieved.

Past research results have indicated that aeration can be an effective tool for odor control (Pain et al., 1990; Sneath et al., 1992; Zhang and Zhu, 2005; Williams et al., 1984; Williams et al., 1989; Zhang et al., 2004). Under aerobic conditions, biodegradable organic materials such as swine manure can be oxidized into stable inorganic end products by aerobic bacteria (Westerman and Zhang, 1997). The nitrogenous compounds in manure are oxidized to nitrite and then to nitrate, enabling the management of excess nitrogen as di-nitrogen (N_2) gas through localized denitrification (Burton et al., 1993). In addition, odorous compounds such as sulfide and mercaptan are also decomposed to form odorless sulfate (Westerman and Zhang, 1997). Work by Williams (1984) quantified the relationship between the offensiveness of odor and the volatile fatty acids (VFAs) concentration in treated pig slurry, a major group of odorous compounds that can be controlled by aerobic treatment. Williams et al. (1984, 1989) also showed how the return of an offensive odor in stored aerobically-treated liquid manure, indicated by the increase in VFA content, was determined by the aerobic treatment regime that the manure had undergone prior to storage. All this information clearly demonstrates that aeration (aerobic treatment) has been proven an effective technique in manure odor control. As such, treatment technologies based on this principle need to be developed and put in use for animal producers to conquer the intractable odor issue.

Mitigation Mechanism:

An anaerobic lagoon, if functioning properly, will usually not produce significant odors. However, due to management problems, many anaerobic lagoons are overloaded so the normal anaerobic digestion process is disrupted and odorous compounds, such as volatile fatty acids, sulfides, indoles, and other odorous substances, are produced in large quantities as a result. These compounds find their way to the atmosphere by surface emission, which can actually be effectively contained by lagoon covers. Using the same concept, a surface aeration unit is developed and aimed at aerating the top liquid in a lagoon to create an oxygenated layer that functions just like a cover to reign in the emission of odors from the lagoon surface. In this paper, such a surface aeration system, composed of a venturi air injectors complex which was tested in both lab- and field-scale experiments for its effectiveness and efficiency in transferring oxygen into the liquid under aeration, is presented. Unlike physical covers, the aerated liquid layer on the surface of a lagoon forms an intangible biological cover that can decompose the odorous compounds before they gain access to the atmosphere, leading to reduced odor emissions.

Applicability:

This technology is best suited for any open liquid manure storages including lagoons, ponds, and earthen storage basins for odor control, regardless of animal species such as swine, poultry, and dairy operations as long as an open liquid manure storage structure is used in the manure handling and storage system. The technique will not be feasibly applied to in-barn manure storages, such as deep pits, because of the potential for increased ammonia emission during the aeration treatment, leading to deterioration of indoor air quality. Figure 1 shows a sketch of the surface aeration system in a manure lagoon and figure 2 is a photo of the installation of a pilot scale unit on a swine manure lagoon in Minnesota during the experiment. A snapshot of the aerator module complex made of six venturi air injectors is presented in figure 3.

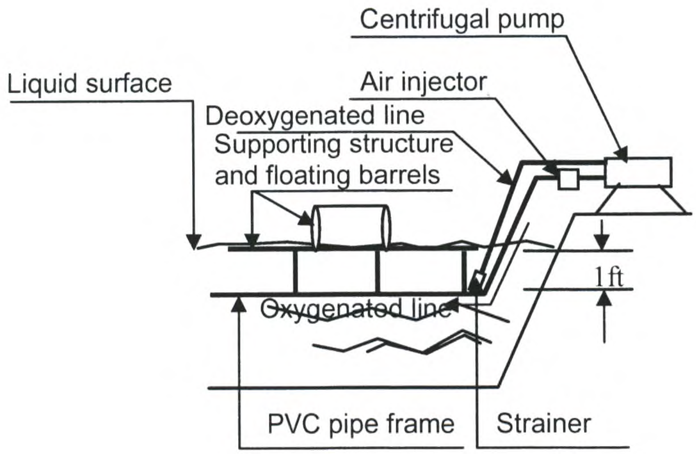

Figure 1. Schematic of a section of the aeration apparatus

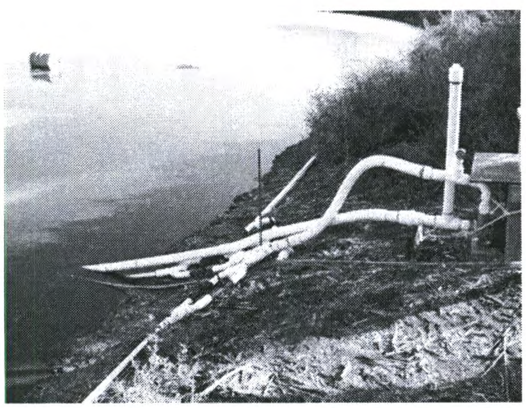

Figure 2. The aerator module in the field test

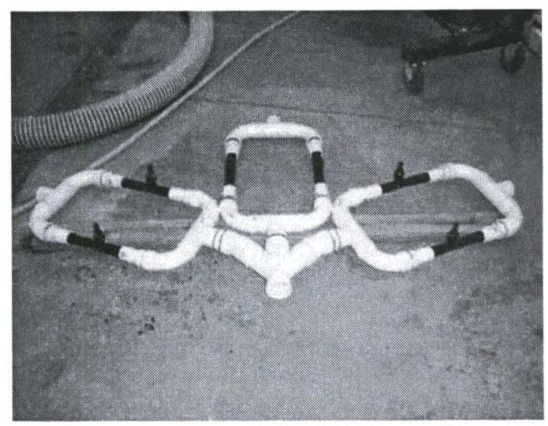

Figure 3. The configuration of the aerator module

As said early, surface aeration is to create an aerated layer in the top lagoon liquid that functions like a biological cover to prevent the odorous compounds from going airborne, thus reducing the quantity and intensity of odor generated by the manure lagoon. Since it is an invisible cover, the additional benefit of this technology may lie in the savings in labor and material costs in constructing and/or placing (replacing) physical covers.

Limitations:

This technology is not meant to completely eliminate odor emission from manure storage facilities due to the fact that it is not expected to function like an impermeable physical cover. Therefore, users of this technology will still see odors emanated from the liquid manure storages, but at a significant reduced level. In addition, the system can work all-year around in warm climate zones after initial installation; however, the piping structure has to be removed from the liquid to avoid damage potentially caused by water freezing during winter in the northern states of the country and replaced into the liquid in late spring or early summer when the lagoon water thaws. In this case, the implementation of the technology may encounter some level of inconvenience.

Cost:

The capital cost of this surface aeration system is relatively inexpensive and all the venturi air injectors are commercially available (under $200/each). For a one-acre lagoon, a total of 18 air injectors are needed, which amounts to about $3,600. Three pumps (1.5 horsepower each) will also be needed (alternatively one 4.5 horsepower pump can be used, too) for the establishment, adding another $1,000 to $1,500 into the budget. The piping structure will cost about $500 in materials and $5,000-$7,000 in construction and installation. In summary, the equipment cost including materials and installation may be anywhere between $10,000 and $15,000 for a one-acre size lagoon.

As for the running cost, the electricity outlay is relatively minimal. For a 4.5 horsepower pump running 24 hours a day and 365 days a year, the power consumption will be 4.5 hp x 0.75 kW/hp x 24 h/day x 365 day/year = 29,565 kWh.

Assuming the price per kWh being at $0.07, the total annual cost for the operation will be 29,565 kWh x $0.07 = $2,070. Considering the particular lagoon where this system was experimented, the production facility has a capacity of 4,000 head finishing pigs, which means that a total of 10,000 pigs could be produced each year, given a yearly production cycle of 2.5. Thus, the treatment cost per pig marketed is only about 21 cents. In addition, the proposed surface aeration system is literally maintenance free with limit needs in checking the functionality of the pumps and strainers.

Implementation:

Information reported here concerning the use of the developed surface aeration technique to control odor emission from liquid manure storages is based on data from a study performed on an actual swine manure lagoon located in Nicollet County in Minnesota. The lagoon, an earthen structure of about 1 acre surface area, receives manure from 4 barns housing finishing pigs all year around. The surface aeration apparatus was designed to cover about 1/3 of the lagoon surface with the uncovered area being used as the control. Since the experiment was conducted in Minnesota, the unit could only be operated between late spring and early fall and was taken out of water afterwards to avoid piping freezing issues. This project is part of a large effort funded by the USDA National Research Initiatives Air Quality Program (project title: A Field-Scale Surface Aeration System to Control Odor from Open Liquid Manure Storage Facilities; Agreement Number: 2006-55112-16639) in developing and evaluating a cost-effective surface aeration system to control odor and gas emissions from liquid manure storage facilities.

Before the field scale surface aeration structure was actually built, an extensive lab-scale experiment aimed at developing an efficient aerator module was carried out at the University of Minnesota Southern Research and Outreach Center at Waseca. The outcome of the numerous lab experiments is the completion of the design of the aerator module currently used in the field experiment. This aerator module has significantly increased the aeration efficiency without increasing the power consumption, leading to the establishment of an aerated layer in top lagoon liquid with a constant level of dissolved oxygen of greater than 0.3 mg/L at a depth 6" from the liquid surface. According to the data collected in last summer, the aerated liquid layer, as expected, worked effectively as a biological cover that prevented odorous compounds from escaping from the liquid, hence the reduction of odor emissions. Based on the air samples collected from both the treated and control areas from the experimental lagoon and analyzed at the Olfactometry Lab in the Bioproducts and Biosystems Engineering Department at the University of Minnesota, the reduction in detection odor threshold has reached about 67% shortly after the start of the aeration operation. More field tests have been arranged and a full evaluation of the system in terms of manure odor control from the same lagoon will be conducted in the coming summer. It is expected that, upon completion of the study, the technology will become mature and ready for adoption by animal producers using lagoons or other open manure storages to reduce odor emissions from their operations.

Technology Summary:

Aeration is a proved technology to reduce odor from animal manure storage facilities. However, the scarce use of this technology by animal producers largely hinges on its prohibitive capital and running costs. To overcome this concern, partial aeration, such as surface aeration, can be an alternative to full aeration to save power usage. The developed surface aeration system that employs a specially designed aerator module that can effectively transfer air into liquid at minimal electricity consumption has been demonstrated in this paper according to field test data and proved to be able to significantly cut down on the odor strength (in odor detection threshold) emitted from the lagoon. The surface aeration system can be run all year around in warm climate zones but can only be operated part of the year in cold climate zones. The maintenance requirement is expected to be minimal and the capital cost for the system is estimated at between $10,000 and $15,000. The annual running cost of the presented surface aeration system is around $2,000 which results in a production cost of about 21 cents per pig marketed.

Additional Resources:

Interested readers may go to www.bbe.umn.edu and click on "publications and frequently asked questions" to get more information on aerobic treatment and surface aeration. An article about this topic also is included in the trade magazine "National Hog Farmer" (vol. 52, issue 12, p.27, 2007). The aerator development process can be found in an article published in a research journal "Applied Engineering in Agriculture" titled "Aerator Module Development Using Venturi Air Injectors to Improve Aeration Efficiency" (vol. 23, issue 5, pp, 661-667).

Acknowledgments:

This paper is based upon work supported by the National Research Initiative Air Quality Program of the Cooperative State Research, Education, and Extension Service, U.S. Department of Agriculture, under Agreement No. 2006-55112-16639.

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As published in the proceedings of:
MITIGATING AIR EMISSIONS FROM ANIMAL FEEDING OPERATIONS CONFERENCE
Iowa State University Extension
Iowa State University College of Agriculture and Life Sciences
Conference Proceedings
Sponsored by:
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Management of Dairy Operations to Prevent Excessive Ammonia Emissions

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Texas A&M University System

Species: Dairy
Use Area: Animal Housing and Manure Storage
Technology Category: Management
Air Mitigated Pollutants: Ammonia

Description:

Dairy operations in the southwestern US are predominantly comprised of two management system; an open-lot system and a hybrid system of open-lots and free-stalls. In an open-lot dairy, cows are housed on un-paved corrals with access to feed bunkers and water tanks. Manure is scrapped, and process generated wastewater from milking parlor and rainfall induced lot runoff are stored in a retention control (lagoons and ponds) structure. In a hybrid system, lactating cows are fed and housed in paved free-stall barns and dry cows and heifers are kept and fed in un-paved corrals. In addition to scraping corral manure, manure from free-stalls is removed by flushing, scrapping or vacuuming. Flushed manure, wastewater from milking parlors and corral runoff are stored in retention control structures. Studies show that agricultural and animal feeding operations contribute considerable amount of ammonia (NH_3) to the atmosphere (Arogo et al., 2001; Anega et al., 2003). Cattle including dairy cows are the largest animal sources contributing to NH_3 emissions. Atmospheric NH_3 is considered to be a precursor to $PM_{2.5}$ (particulate matter with aerodynamic diameter less than 2.5 µm) (Anega et al., 2001; Gupta et al., 2003) and PM ($PM_{2.5}$ and PM_{10}) is one of the six criteria pollutants for which National Ambient Air Quality Standards (NAAQS) were developed by the USEPA.

Until recently, no comprehensive data was available on contribution of NH_3 emissions to the atmosphere from dairies in the mild southwestern climate of the US. The first step towards prevention of excessive emissions of NH_3 from southwestern dairy operations is to quantify them from different sources within a facility to assess how open-lot and hybrid dairy management systems, manure handling and storage practices and weather conditions impact NH_3 emissions. Once this information is available, specific on-farm practices may be explored and adopted to reduce excessive NH_3 emissions from "critical sites" within the operation.

Recently published (Mukhtar et al., 2008) and unpublished data from open-lot and free-stall dairies in Texas provided the following insight into NH_3 emissions from the ground level area sources of these dairies.

Open-lot Dairy (~2000 lactating cows)

- Total surface area of open-lot corrals = 103,000 m^2 (25.4 ac)
- Total surface area of primary (6,275 m^2) and secondary (46,094 m^2) lagoons = 52,370 m^2 (13 ac)
- Separated solids pile are = 500 m^2 (0.12 ac)
- Milking parlor crowding area = 500 m^2 (0.12 ac)

<u>Major Findings on NH_3 Emissions from Open-lot Dairy</u>
- Summer emissions were ~ 47% higher than winter emissions
- Lagoons contributed ~ 37 % to summer emissions and ~ 5% to winter emissions
- Corrals contributed ~ 63% to summer emission and ~95% to winter emissions
- Emissions from separated solids and milking parlor were negligible
- Emissions from open-lot corrals varied with cow density and resulting manure loading
- During summer feeding and shaded areas within an open-lot had significantly higher emission than the rest of the lot

Hybrid Dairy (~2000 lactating cows)
- Total surface area of open-lot corrals = 38,000 m^2 (9.4 ac)
- Total surface area of on-site compost windrows = 18,800 m^2 (4.6 ac)
- Total surface area of free-stalls = 10,000 m^2 (2.5 ac)
- Total surface area of primary (16,600 m^2) and secondary (16,500 m^2) lagoons = 33,100 m^2 (8.2 ac)
- Separated solids pile are = 110 m^2 (0.03 ac)
- Milking parlor crowding area = 925 m^2 (0.23 ac)

Major Findings on NH_3 Emissions from Hybrid Dairy

- Summer emissions were more than 50 % higher than winter emissions
- Lagoons contributed ~ 65 % to summer emissions and ~ 2% to winter emissions
- Free-stalls contributed ~ 36% to winter emissions and ~ 22% to summer emissions
- Corrals contributed ~ 11% to summer emission and ~ 26% to winter emissions
- Actively composting manure solids had significantly higher emissions than mature compost
- Feeding area within a free-stall contributed higher emission than bedding and watering areas

Mitigation Mechanism:

Reduction in NH_3 emissions from dairy waste as a result of reduced crude protein in dairy diets reducing urinary urea-N levels is well documented. Studies by Misselbrook et al. (2005) and others have shown reduced NH_3 emissions when manure from cows fed a reduced crude protein was applied to land. Ammonia volatilization rate from dairy manure and processes generated waste water exposed to the environment depends upon total ammonium concentration, pH, moisture content, air velocity, temperature etc. Mitigation technologies such as lowering poultry litter pH with alum to reduce NH_3 emissions from enclosed poultry housing has been shown to be effective (Moore et al., 2003). But dispirit housing systems (naturally ventilated facilities with much larger surface area compared to poultry barns) and manure management practices may render alum amendment to manure and wastewater to be impractical and in-effective. To date, an exhaustive search on existing or new technologies to reduce NH_3 emissions from the two southwestern US dairy production systems has resulted in no such information.

Applicability:

The management practices discussed in the Implementation section apply to mitigation of excessive NH_3 emitting from open-lot corrals, lagoons, and free-stall surface of dairy operations.

Limitations:

Lack of excess fresh or recycled water for frequent flushing, lack of extra storage capacity of retention control structures (RCS) to store additional flushed effluent, termination of on-site composting or moving the composting operation off-site etc. will be some of the limitations to implementing mitigation practices.

Cost:

No specific costs were estimated for implementing management practices. Costs range from minimal to substantial, depending upon the practice considered for reducing excessive NH_3 emissions. For example, doubling the frequency of flushing a free-stall will require pumping more fresh or recycled water and increasing the capacity of an existing RCS or building a new one adding much higher costs for implementing frequent flushing. Another substantial cost may be covering RCS to reduce NH_3 emissions. These RCS range in surface area from 2 to 5 or more hectares. Unless an economic incentive is provided, even partially covering these structures will be costly.

Implementation:

Data on NH_3 emissions measurements at the two southwestern dairy management systems; a free-stall and a hybrid system showed that following are the critical sites requiring implementation of practices to reduce excessive emission.

- Retention control structures (RCS include lagoons and ponds) during summer
- Feeding and shaded areas of open-lot corrals with higher cow density and manure loading
- Free-stalls
- Active compost windrows

Our findings suggest that during the summer season, management practices such as frequent removal of manure from critical sites of manure accumulation will be the key to reducing excessive NH_3 emissions from free-stall and hybrid dairies. These practices include frequent flushing of manure lanes, frequent scrapping of feeding and shaded areas of open-lot corrals, and possibly, moving the compost system off site. Land application of RCS effluent during cooler temperatures to avoid solar heating and where possible, incorporation or direct injection of effluent will prevent excessive loss of nitrogen and NH_3. Proper management of RCS is highly critical especially during summer season because these manure storage and treatment structures can contribute as much as two thirds of the total NH_3 emitted from dairy operations. Unfortunately, due to their large "foot print" covering or conversion of RCS to anaerobic digesters to reduce gaseous emissions to the atmosphere is very costly.

Technology Summary:

Ammonia emissions data from open-lot and hybrid (combination of free-stalls and open-lots) dairies in the milder climate of southwest US indicated that summer emissions from these facilities were nearly 50% higher than winter emissions. Due to their large surface areas, lagoons and open-lot corrals were the highest contributors of NH_3 emissions but little NH_3 was emitted from lagoons during the winter months. Within open-lot corrals and free-stalls, NH_3 emissions increased with greater manure loading and actively composting manure emitted considerable NH_3 even during winter months. While reduction in dietary N intake is known to reduce manure nitrogen content, no information on technologies to mitigate NH_3 emissions from these two types of dairy operations is available. Management practices such as frequent removal of manure from heavily loaded areas of open-lots and free-stalls, proper management of lagoons and other manure storage structures, summer irrigation of lagoon effluent during cooler temperatures, and where possible, incorporation or injection of effluent will help reduce excessive NH_3 emissions. While frequent scrapping of targeted open-lot corral areas can be achieved without substantial increase in costs, covering lagoons to reduce NH_3 emissions will be a very expensive mitigation practice.

Acknowledgments:

Data on NH_3 emissions from open-lot dairy and hybrid dairy was collected through a research funded by a grant from the USDA–Cooperative State Research, Education, and Extension Service Project No. 2006-06009.

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As published in the proceedings of:
MITIGATING AIR EMISSIONS FROM ANIMAL FEEDING OPERATIONS CONFERENCE
Iowa State University Extension
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Characterizing Ammonia Emissions from Swine Farms in Eastern North Carolina – Part I. Conventional Lagoon and Spray Technology for Waste Treatment

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Species:	Swine
Use Area:	Manure Storage
Technology Category:	Anaerobic Digestion and Manure Injection
Air Mitigated Pollutants:	Ammonia

Description:

The conventional lagoon and spray technology (LST) is the current system predominantly used in North Carolina to manage pig waste (Aneja et al., 2008). It consists of anaerobic lagoons to store and biologically treat pig waste (~99.5% liquid). Effluent from the lagoons are sprayed on surrounding crop fields as a nutrient source. Four distinct components and associated processes of LSTs release NH_3 to the atmosphere: (1) production houses, (2) waste storage and treatment systems such as lagoons, (3) land application through injection or spraying, and (4) biogenic emissions from soils and crops (Aneja et al., 2001).

Mitigation Mechanism:

The manure is treated under aerobic conditions and the treated manure is sprayed on the crops as a source of fertilizer. Crops use the nitrogen in the manure as a source of nutrients. Additionally some of the NH_3 emissions are reduced by the storage of waste in a sludge composition at the bottom of the lagoon. The primary mitigation mechanism would be biological catabolism of compounds contributing to the relatively high carbon loading manure effluent flushed into the lagoons.

Applicability:

Where permittable, lagoon spray technology, as described in this study, is applicable for swine production systems that would have flush systems and environmental (climatic) conditions similar to North Carolina. Ammonia flux measurements were made during two different seasons at two conventional (*i.e.* LST) swine farms in eastern North Carolina. The two finishing conventional farms were Stokes and Moore Brothers farms, respectively. Our measurements of NH_3 flux were limited to two two-week long periods, representing warm and cold seasons. The fall and winter intensive measurements were conducted during September 9-October 11, 2002 and January 6-Feburary 2, 2003, respectively.

Ammonia fluxes from the waste storage lagoons were measured by a dynamic flow-through flux chamber system interfaced to an environmentally controlled mobile laboratory. The on-site measurement period for each season was limited to two weeks at the experimental farm sites. Ammonia fluxes from the animal storage waste lagoons, other water holding structures, and spray fields at the two conventional and several potential Environmentally Superior Technology (EST) sites were measured by the dynamic flow-through flux chamber system. The times of spray did not occur close to our measurement periods.

For ammonia flux measurements using the dynamic chamber system, sampling consists of measuring the gaseous ammonia concentration of the sample stream exiting the dynamic chamber system on a continuous basis. Simultaneous continuous measurements of ambient ammonia concentration, lagoon temperature, lagoon pH, air temperature, relative humidity, wind speed, wind direction, and solar radiation were also made and recorded. One to three samples of lagoon waste adjacent to the floating platform were collected each day and stored near $0^{o}C$ during ammonia flux measurement periods in order to determine the concentration of total Kjeldahl nitrogen (TKN), and total ammoniacal nitrogen (TAN) in the liquid lagoon effluent.

Barn emissions were measured using an Open-Path Fourier Transfer Infrared (OP-FTIR) spectroscopy system. NH_3 emissions from barn houses were estimated from average ammonia concentration measured by OP-FTIR and the rated flow rate for the fan size and setting. Operation of fans were monitored to determine when they were on or off during the entire sampling period. Estimated flow rates from naturally ventilated barns were calculated using wind velocity readings.

The average lagoon NH_3 fluxes for the two conventional farms during the fall and winter months were 2017±751 and 262±100 g-N m^{-2} min^{-1}, respectively. These averages were comparable to those found in the previous study from a typical swine farm (Farm #10) in North Carolina (Aneja et al., 2000).

Typical diurnal variation of lagoon NH_3 flux was observed during the measurement periods. The NH_3 flux increased exponentially with increasing lagoon temperature, and the best-fitted regression relationship between the two is:

$$\log_{10}(N) = 0.051T_l + 1.943 \quad (1)$$

($R^2 = 0.82$ and $p < 0.0001$), Here, F denotes the average NH_3-N emission from the conventional lagoon in µg min^{-1}/1000 kg-lw, where T_l is the lagoon temperature in °C, and D is a hot-air variable that is equal to zero if lagoon is warmer than air, but is equal to $\Delta T = T_a - T_l$ when $T_a > T_l$ and T_a is air temperature in °C at 2m height.

This regression relationship showed very good agreement with that of Aneja et al.(2000) based on Farm #10 flux measurements.

Relationships between lagoon NH_3 flux and chemical parameters, such as pH, TKN and TAN of lagoon waste were also examined. The lagoon pH stayed in a relatively narrow range from 7.7 to 8.5 during fall and winter seasons. No significant correlation between pH and lagoon NH_3 flux was observed during the experimental periods at either farm. Additionally, TKN and TAN concentrations were not found to be significantly correlated with lagoon NH_3 flux over the entire data set. Although positive correlations of TKN and TAN with NH_3 flux were found in individual seasons.
The influence of atmospheric environmental parameters on lagoon ammonia flux was investigated. Ammonia flux was found to be significantly correlated with lagoon temperature and the difference between air and lagoon temperature ($\Delta T = T_a - T_l$). ΔT is considered a measure of near-surface atmospheric stability, and is known as the 'hot air'effect. The multiple regression equation for the average lagoon emissions at the two conventional farms is:

$$\text{Log}_{10} F = 3.8655 + 0.0449Tl - 0.05946D \quad (2)$$

in which T_l is the lagoon temperature and D is the 'hot air' variable. F is the the normalized ammonia emission rate. T_l and D are expressed in units of °C, and F in units of kg-N min^{-1} $(1000kg\ lm)^{-1}$

Barn emissions were measured for one season at Stokes farm (naturally ventilated) and two seasons at Moore farm (mechanically ventilated). Emissions normalized by live animal mass were found to be comparable to other studies. The statistical-observational model developed and described herein and the barn emissions protocol is proposed as a valid and objective approach to be used to compare the emissions from potential environmental superior technologies in order to evaluate the effectiveness of such technologies.

Limitations:

LSTs has been shown to be an effective and affordable biological treatment technology for processing high organic concentration waste streams typical of flushed animal manure. Environmental issues, including ammonia emissions, however have been identified with this system relative to long term sustainability. In addition, some states and regions, including North Carolina, have regulatory restrictions permitting new or expanding farm facilities that utilize LST

Cost:

Ten year annualized costs for a "Baseline" LST for a 4,320-head finishing farm using a pit recharge system of manure removal is predicted to be approximately $90 per 1,000 lbs. steady state live weight per year (Williams, 2006. see Table 8a, page 58).

Implementation:

Implementation of LST should be consistent with regulatory limitations noted above.

Technology Summary:

The cost of an LST is low, and has the benefit of being a source of nutrients for crops. It is though perceived that it has a large negative effect on the environment as a result of emissions of ammonia, odor, and pathogens. There are environmental concerns in North Carolina, particularly in eastern North Carolina where approximately 6 million hogs reside in a six county region. As a result the State of North Carolina is examining the possible use of alternative technologies known as potential Environmentally Superior Technologies (ESTs) to reduce the environmental impact. The effectiveness of the ESTs are evaluated by a comparison to the current LST emissions. The comparison will be achieved by the use of a statistical-observational model based on measurements.

Additional Resources:

Additional and detail information re materials and methods and cost information is available at http://www.cals.ncsu.edu/waste_mgt/

Acknowledgments:

Financial support provided by the North Carolina State University Animal and Poultry Waste Management Center is greatly appreciated. We sincerely acknowledge the help and support provided by Ms. Lynn Worley-Davis. We thank the technology PIs, farm owners, Cavanaugh & Associates, and Mr. Bundy Lane, C. Stokes, and P. Moore for their cooperation. We acknowledge the discussions and gracious help provided by Dr. John Fountain, Dr. Richard Patty, Dr. Ray Fornes, and Dr. Johnny Wynne of North Carolina State University. We thank Mark Barnes, Guillermo Rameriz, and Rachael Huie. We also thank Mr. Hoke Kimball, Mr. Mark Yurka, and Mr. Wade Daniels all of NC Division of Air Quality for their support. Thanks to Dr. Bruce Gay, US EPA; and Dr. Joette Steger, for their review of Project OPEN. Financial Support does not constitute an endorsement by the APWMC of the views expressed in the report, nor does mention of trade names of commercial or noncommercial products constitute endorsement or recommendation for use.

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As published in the proceedings of:
MITIGATING AIR EMISSIONS FROM ANIMAL FEEDING OPERATIONS CONFERENCE
Iowa State University Extension
Iowa State University College of Agriculture and Life Sciences
Conference Proceedings
Sponsored by:
NRI Air Quality Extension & Education
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Characterizing Ammonia Emissions from Swine Farms in Eastern North Carolina – Part II. Potential Environmentally Superior Technologies for Waste Treatment

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Species: Swine
Use Area: Manure Storage, Manure Treatment
Technology Category: Anaerobic digestion, aerobic treatment, solid separation/gasification, solid separation/off site removal
Air Mitigated Pollutants: Ammonia, Odor, Pathogens

Description:

The need for developing environmentally superior and sustainable solutions for the management of animal waste is vital for the future of animal farms in North Carolina, the U.S. and the world. In addressing that need, the North Carolina Attorney General initiated the development, implementation, and evaluation of environmentally superior swine waste management technologies (ESTs) that would be appropriate to each category of hog farms in North Carolina. The agreements define "Environmentally Superior Technology or Technologies" as any technology, or combination of technologies that (1) is permittable by the appropriate governmental authority; (2) is determined to be technically, operationally, and economically feasible for an identified category or categories of farms (to be described in a technology determination); and (3) meets the following performance standards:

- Eliminates the discharge of animal waste to surface waters and groundwater through direct discharge, seepage, or runoff;
- Substantially eliminates atmospheric emission of ammonia;
- Substantially eliminates the emission of odor that is detectable beyond the boundaries of the parcel or tract of land on which the swine farm is located;
- Substantially eliminates the release of disease-transmitting vectors and airborne pathogens; and
- Substantially eliminates nutrient and heavy metal contamination of soil and groundwater.

Program OPEN (Odor, Pathogens, and Emissions of Nitrogen) was initiated as an integrated study of the emissions of ammonia, odor and odorants, and pathogens from potential ESTs for swine facilities. Its main purpose was to evaluate potential ESTs that have been developed and implemented under an agreement between the North Carolina Attorney General and the participating companies that own approximately 10% of the swine farms in North Carolina, employing the conventional lagoon and spray technology (Aneja et al., 2008 a,b). Under this program, ESTs implemented at selected swine facilities were evaluated to determine if they would be able to substantially reduce atmospheric emissions of NH_3, odor, and pathogens. This study focuses on the emissions of nitrogen in the form of NH_3 from different components/processes involved in hog waste handling and treatment, including waste storage lagoons, hog houses, and spray fields at eight selected EST sites. These are described below in the following format; name of the farm where the potential EST was employed, type of technology, and brand name where applicable.
(1) Barham Farm – in-ground ambient temperature anaerobic digester/energy recovery/greenhouse vegetable production system; (2) BOC # 93 Farm -Up-flow biofiltration system - EKOKAN ; (3) Carrolls Farm- Aerobic Blanket System - ISSUES-ABS; (4) Corbett # 1 Farm - Solids separation/gasification for energy and ash recovery centralized system-BEST; (5) Corbett # 2 Farm – solid separation/ reciprocating water technology- ReCip; (6) Vestal Farm- Recycling of Nutrient, Energy and Water System-ISSUES-RENEW; (7) Goshen Ridge Farm (Solids Separation/nitrification-denitrification/soluble phosphorus removal/solids processing system (Super Soils); (8) Red Hill Farm ('Closed Loop' Swine Waste Treatment System). The first six EST sites contain anaerobic lagoons as part of their system, however EST # (7) and (8) do not contain anaerobic lagoons as part of their system. These potential ESTs were evaluated during two seasons (cool and warm), and the results are compared and contrasted with data from two conventional LST swine farms (Moore Farm and Stokes Farm).

The conventional lagoon and spray technology (LST), is the current system used in North Carolina to manage pig waste. It consists of anaerobic lagoons to store and biologically treat pig waste (~99.5% liquid). Effluent from the lagoons is sprayed on surrounding crop fields as a nutrient source. Four distinct components and associated processes of LSTs release NH_3 to the atmosphere: (1) production houses, (2) waste storage and treatment systems such as lagoons, (3) land application through injection or spraying, and (4) biogenic emissions from soils and crops.

Mitigation Mechanism:

(1) Barham Farm – in-ground ambient temperature anaerobic digester/energy recovery/greenhouse vegetable production system. Mitigation of emissions occurs predominately due to anaerobic catabolism of volatile organic compounds as well as physical containment (preventing emissions) due to the impermeable cover component of the in-ground digester. Post anaerobic treatment the digested effluent is further process in biological trickling filters thus enhancing biological nitrification of ammonia. This potential EST has an in-ground ambient digester comprised of a covered anaerobic waste lagoon. The primary lagoon was covered by an impermeable layer of 40 mm thick high-density polypropylene that prevented gaseous methane and other gases and odor from escaping into the atmosphere during the digestion process. Methane gas that is produced during the digestive process was extracted and burned into a biogas generator to produce electricity. Heat from the generator was captured and used to produce hot water that was used by the farm in its production activities. Effluent from the digester (covered lagoon) flowed into a storage pond, with a surface area of 4,459 m^2. This storage pond was formerly part of the primary anaerobic lagoon before the digester was built. A portion of this effluent was further treated via biofilters, whose purpose was to convert ammonium to nitrate in the effluent. This nitrified effluent was then used to flush out the hog production facilities, and the excess effluent was channeled into the larger overflow pond, with a surface area of 19,398 m^2. A heavy polymer baffle separated the overflow and storage ponds. The overflow pond was used to store rainwater and overspills from the storage pond. Water from the overflow pond was also pumped into a nitrification biofiltration system where the nutrients in the treated effluent were used to fertilize vegetables grown in greenhouses adjacent to the swine production facility.

(2) BOC # 93 Farm -Up-flow biofiltration system – EKOKAN. Mitigation of emissions occurs predominately due to aerobic catabolism of volatile organic compounds and biological nitrification of ammonia within the aerated biofilter. The EKOKAN waste treatment system consists of solids/liquid separation and biofiltration of the liquid with upflow aerated biological filters. Five finishing barns are connected to the waste treatment system, and the barn pits are emptied automatically in sequence. Wastewater from the barn pits is released to a solids separation unit. Coarse solids are separated from the wastewater using a screen separator (TR Separator). After the solids/liquid separation process, the liquid is pumped to a 40,000-gallon equalization tank. Liquid flows from the equalization tank by gravity and passes through first-stage and second-stage aerated biofilters connected in series (two sets). Wastewater flows upward through the biofilters, and air is supplied at the bottom of each biofilter with blowers. The biofilter tanks are covered, and air and any excess foam from the aerated treatment are routed through PVC pipes to exit points over an anaerobic lagoon. The biofilters are backwashed periodically to remove excess biosolids. Treated effluent from the biofilters flows by gravity to a storage basin, with a portion of the treated effluent being recycled to the solids separation basin, from which it is pumped to the equalization tank, which has a surface area of 28.3m^2. Water is pumped from the storage basin to the barns to refill the pits. At this site, the anaerobic lagoon that receives manure from 10 barns was partitioned using plastic curtains into three sections, with one section much larger than the other two. The larger section receives manure from five barns not connected to the EKOKAN treatment system. One of the smaller sections receives any overflow from the solids separation basin, the separated solids, and the backwashed biosolids that are removed from the biofilters. This is known as the biosolids lagoon and has a surface area of 3229.2m^2. The other small section receives the treated effluent from the biofilters. This is known as the treated effluent lagoon and has a surface area of 1614.6m^2.

(3) Carrolls Farm- Aerobic Blanket System - ISSUES-ABS. Mitigation of emissions occurs predominately due to aerobic catabolism of volatile organic compounds and biological nitrification of ammonia at the surface of the aerobic blanket. The waste stream in the proposed EST flows from the houses to a primary anaerobic lagoon equipped with the Aerobic Blanket System (ABS). This is known as the ABS lagoon and has a surface area of 3304.8 m^2. The ABS consists of a fine mist of treated swine waste that is applied every 15 minutes to the surface of the anaerobic lagoon. During both evaluation periods, only half of the anaerobic lagoon was being treated by the ABS. The treated swine waste arises from an aeration treatment that takes place in an adjoining water-holding structure (aerobic digester). Waste from the anaerobic lagoon flows into an aerobic digester (IESS aeration system). This is referred to as the west side of the aerated lagoon and has a surface area of 5068.8 m^2. This portion of the basin is sectioned off with a plastic barrier. The aerated waste eventually flows into the sectioned-off portion of the aeration treatment basin. This is known as the east side of the aerated lagoon, and has a surface area of 6010.2 m^2. The waste is then used to flush the animal houses, and supplies the treated water for the ABS. During the first evaluation period, the IESS aeration system was not functioning and treated waste for the ABS was derived by using two aeration treatment tanks. For the

second evaluation, the aeration treatment basin was operating as designed. Only waste from finishing houses 5 – 13 flowed into the ABS-equipped anaerobic lagoon. Waste from the remaining farrow and weaning houses flowed into a separate lagoon. These houses and their accompanying lagoon were not included in the evaluation of the EST.

(4) Corbett # 1 Farm - Solids separation/gasification for energy and ash recovery centralized system-BEST. Mitigation of emissions occurs predominately due to physical containment and recovery of the solids which are removed from the site for further processing (gasification) – this process reduces the substrate available for biological synthesis of volatile organic compounds. Manure flushed from the barns flows first to a collection pit, then to an above-ground feed tank, and then to a screw press separator on a raised platform. The separator has a screen with .25 millimeter openings. The liquid that flows through the screw press separator screen flows to a second feed tank, which has a surface area of 27.1 m^2, then to two tangential flow gravity settling tanks sited parallel to each other. Each tangential flow settling system consists of a 2.2-meter diameter tank with a cone bottom followed by a 1.2-meter diameter sludge thickening tank, also with a cone bottom. Tangential flow in the first tank causes solids to concentrate in the center of the tank and settle down to the bottom. This settled slurry is then pumped to the second tank for sludge thickening. For about 10 minutes every hour the settled slurry from the second tangential flow settling tank is pumped back to the tank that feeds the screw press separator, where the settled slurry is combined with the flushed manure that is being pumped to the screw press separator. The treated waste and any overflow go to a stabilization and treatment pond, which has an area of 8291.9 m^2.

(5) Corbett # 2 Farm – solid separation/ reciprocating water technology- ReCip. Mitigation of emissions occurs predominately due to physical containment and recovery of the solids which are removed from the site for further processing – this process reduces the substrate available for biological synthesis of volatile organic compounds. In addition, the reciprocating wetland cells enhance biological catabolism of volatile organic compounds and support the process of nitrification / denitrification thus reducing ammonia emissions. The ReCip encompasses two cells, or treatment basins, filled with media (proprietary technology), that would alternately drain and fill on a cyclic basis. The draining and filling cycles created aerobic, anaerobic, and anoxic conditions within the cells, providing both biotic and abiotic treatment processes to promote nitrification and denitrification. The treatment process was preceded by a solids separation step. The solid waste and the treated liquid waste went into individual lagoons, which had surface areas of 2,601 m^2 and 2717 m^2, respectively. The ReCip project at the evaluation time was designed to treat only the liquid portion of the swine waste.

(6) Vestal Farm- Recycling of Nutrient, Energy and Water System-ISSUES-RENEW. Mitigation of emissions occurs predominately due to anaerobic catabolism of volatile organic compounds as well as physical containment (preventing emissions) due to the impermeable cover component of the in-ground digester. Post anaerobic treatment some of the digested effluent is further process in an aeration basin thus enhancing biological nitrification of ammonia. The RENEW System employs a mesophilic digester as well as aeration and wastewater filtering and disinfection systems. This project also incorporated a microturbine generator. For this system, the waste first flows from the pig barns to equalization and concentrator tanks, which serve to produce a thickened liquid. This liquid then flows to a mesophilic digester. The digester, which operates at a temperature of 95 degrees F, produces biogas, which is used to fuel the microturbine generator. The generator produces electricity, which is sold and used on the electric power grid. The waste stream then flows to a polishing storage basin, which has a surface area of 22,636.0 m^2, then to an aerobic digester, also called a nitrification pond, which has a surface area of 1880.6 m^2. A portion of the waste stream then flows back to the polishing storage basin, where it is used to flush the pig barns and is sprayed on crop land if necessary. The remaining portion of the waste stream flows through a filtration system. The filtration system consists of sand carbon filters and reverse osmosis. The water is then disinfected using ozonation and ultraviolet light. Filtered and disinfected water is then returned to the pig barns, where it is used as drinking water for the pigs.

(7) Goshen Ridge Farm (Solids Separation/nitrification-denitrification/soluble phosphorus removal/solids processing system (Super Soils)). Mitigation of emissions occurs predominately due to physical containment and recovery of the solids which are flocculated and mechanically concentrated and removed from the site for further processing – this process reduces the substrate available for biological synthesis of volatile organic compounds. In addition, an aeration component enhances biological catabolism of volatile organic compounds and supports the process of nitrification / denitrification thus reducing ammonia emissions. The treatment system employed at Goshen Ridge Farm, known as Super Soils, treats the liquid portion of the waste. The liquid treatment begins with separation of the solid and liquid portions of the waste stream. Solids separation is accomplished using polyacryalmide, a flocculating agent.
The liquid portion of the waste stream flows between tanks in a circulating loop undergoing denitrification as a result of anaerobic activity in one tank, and nitrification through the use of concentrated nitrifying bacteria in the second tank under aerobic conditions. Nitrogen is removed from the waste stream during this stage of the process. The liquid then flows to a settling tank, where phosphorus is removed through the addition of calcium hydroxide and a dewatering bag system. Calcium phosphate, which has value as a fertilizer, precipitates out during this process, providing a value-

added product. During phosphorus removal, the pH of the liquid is raised to 10.5 using lime, which precipitates the soluble P and disinfects the effluent. Roughly 80 percent of the liquid is recycled through the hog houses, while 20 percent is used to irrigate crop fields.

(8) Red Hill Farm ('Closed Loop' Swine Waste Treatment System). Mitigation of emissions occurs predominately due to physical containment and recovery of the solids which are removed from the site for further processing – this process reduces the substrate available for biological synthesis of volatile organic compounds. In addition, this system has a chemical sanitation component which reduces the microbial population that may be contributing to the synthesis of volatile organic compounds. The EST at Red Hill farm was provided by 'Environmental Technologies'. This EST is described as a "closed-loop" system, and its primary objective is to treat the liquid fraction of the waste in such a way that it can be used both for flushing the hog barns and for hog drinking water. This could eliminate the need for the traditional hog waste lagoon. A flush system is used for removing the manure from the barns, which, prior to installation of the treatment system, flushed the waste into a lagoon. The first step in the closed loop process is collection of the waste in an "equalization" or buffering tank. The waste in the tank is continuously pumped to an inclined separator where the solids are collected and further treated. The liquid collected from the separator is injected with a polymer flocculant and sanitizer/disinfectant and pumped into a settling tank, where flocculated solids collect at the bottom over a period of approximately four hours.

Most of the liquid fraction from the settling tank is returned to the hog barns for re-use as flush water. When the flush tanks are full, however, excess water is pumped to a tertiary treatment system. This system provides filtration and aeration and is housed in a septic tank. The treated water is blended with well water to achieve a dissolved solids content that is consistent with human drinking water standards for use as hog drinking water. Solids from the settling tanks are combined with the solids from the inclined separator for further treatment.

Applicability:

The environmental performance studies for all of these systems were conducted on swine production facilities in North Carolina. While the applicability of some of these systems may be appropriate for "deep pit" systems, they were predominately designed for "plug flow" and higher volume "flush" systems characteristic of North Carolina swine production systems; for the purpose of this evaluation study all of the systems should be considered applicable to typical North Carolina systems. At each environmentally superior technology and conventional site, the monitoring of ammonia emissions was limited to about two two-week periods, representing both a warm and a cool season. It was suggested that the estimated emissions from an environmentally superior technology for each measurement period be compared with the estimated emissions from conventional sites. However, since measurements at different sites were made at different times of the year, environmental conditions are likely to be different at different sites, even during a representative warm or cool season. Thus, there is a need for accounting for these differences in our relative comparisons of the various alternative and conventional technologies.

A rational basis for this adjustment for somewhat different environmental conditions is the development of a statistical-observational model based on multiple regressions. This is developed between ammonia emissions and measured environmental parameters at the two conventional sites. Such a comparison does not require highly uncertain extrapolations of emissions at EST sites beyond the two measurement periods. It also provides a sound basis for ranking the various ESTs based on their comparisons with conventional sites for each of the warm and cold seasons. Relationships between NH_3 flux and lagoon temperature, pH, total Kjeldahl nitrogen (TKN), and total ammoniacal nitrogen (TAN),as well as certain environmental parameters are examined in Aneja et al.(2008 a,b). Over a relatively wide range of lagoon temperatures (~ 2°C to ~35°C) and lagoon - air temperature differences that were observed during the fall and winter field campaigns at both conventional farms. The multiple regression equation based on flux measurement data from two conventional farms is given as:

$$\mathrm{Log}_{10}F = 3.8655 + 0.04491(T_l) - 0.05946(D). \qquad (1)$$

Here, F denotes the average NH_3-N emission from the conventional lagoon in $\mu g\ min^{-1}/1000$ kg-lw, where T_l is the lagoon temperature in °C, and D is a hot-air variable that is equal to zero if lagoon is warmer than air, but is equal to $\Delta T = T_a - T_l$ when $T_a > T_l$ and T_a is air temperature in °C at 2m height. This statistical-observational model was used to estimate the projected NH_3-N flux from lagoons at the LST baseline farms to compare with the measured NH_3-N flux from water-holding structures at an EST site, for the average values of T_l and D observed at the latter.

Aneja et al. (2008 a,b) describes the development of the statistical-observational model in more detail. Estimated ammonia emissions from animal houses at a potential EST were compared to the estimated ammonia emissions from similar houses at a conventional farm (either Moore Farm-tunnel ventilated, or Stokes Farm-naturally ventilated), depending on the type of the house ventilation used at the EST farm, for the same season. Both EST emissions and conventional NH_3 emissions were normalized by nitrogen excretion rate (E) for the farm, and are called %E. Based on the nitrogen mass balance equation with given animal feed information, nitrogen excretion rate (*E*) in unit of kg-N wk^{-1} (1000 kg-*lw*)$^{-1}$ was determined using the following equation:

$$E = \frac{F_c \times N_f \times (1 - e_r)}{\overline{w}} \times 1000 , \qquad (2)$$

where F_c is the feed consumed (kg pig^{-1} wk^{-1}), N_f is the fraction of nitrogen content in feed, e_r is the feed efficiency rate (ratio of average gain of nitrogen to nitrogen intake) (PigCHAMP, 1999), and $\overline{w}$ is the average live animal mass (kg/pig). Nitrogen excretion and NH_3-N emissions at each farm was calculated in the same units (kg-N wk^{-1} (1000 kg-*lw*)$^{-1}$), thus, %E represents the loss rate of ammonia from a source, as a percentage of N-excretion rate. A potential EST was evaluated by comparison of %E value from the EST (%E_{EST}) farm to %E value from a baseline conventional farm (%E_{CONV}), and percent reduction of NH_3-N can be estimated as

$$\%\ reduction = \frac{(\%E_{CONV} - \%E_{EST})}{\%E_{CONV}} \times 100 \qquad (3)$$

Such percentage reductions can be estimated, separately for water-holding structures, animal houses/barns, *etc.*, as well as for the whole EST farm. An algorithmic flow diagram for the evaluation of NH_3 emissions from water holding structures at the EST farms is shown in Figure 1.

To calculate the total % reduction, the sum of projected and measured emissions was taken for the water-holding structures and barns. These numbers were used to calculate total % reduction using the same process that was applied individually for water-holding structures and barns. Table 1 shows the summary of the total NH_3 emissions measured for six of the eight EST farms (farms that contained anaerobic lagoons as part of their system), along with the projected emissions from the LST farms, and the % reduction values for their evaluation of potential N reduction. Five out of six farms showed varying amounts of % reductions in NH_3 emissions for both experimental periods. One of the five ESTs showed an appreciable % reduction in NH_3 emissions for both periods. The technology employed at [illegible]ett # 1 had the highest % reductions of 71.8 and 66.0 for the warm and cool seasons, respectively. However, based on our evaluation results and analysis, and available information in the scientific literature, the evaluated alternative technologies may require additional technical modifications to be qualified as unconditional EST relative to ammonia emissions reductions.
Two potential ESTs with no conventional anaerobic lagoon component were evaluated to determine if they would substantially reduce atmospheric emissions of ammonia at the hog facilities and meet the performance standards as compared to estimated or projected emissions from the conventional lagoon and spray technology used at two selected hog farms in two different (warm and cool) measurement periods. Table 2 shows the summary of the water-holding structure NH_3 emissions measured from EST farms, projected emissions from the water-holding structures at the conventional (LST) farms, and % reduction values for their evaluation of potential N reduction.

Both farms showed substantial reductions in NH_3 emissions from their water-holding structures. The Environmental Technologies closed loop system had the largest reductions, with reduction of 99.4% and 99.98% for the cool and warm season, respectively. Super Soils technology had a reduction of 94.7% in the cool season, and 99.0% in the warm season. This study did not address the potential reductions in odor and pathogens that were evaluated by other scientists in the OPEN project (Williams, 2006). Under the conditions reported herein these two potential ESTs meet the criteria established for ammonia emissions as described for ESTs (Williams, 2004).

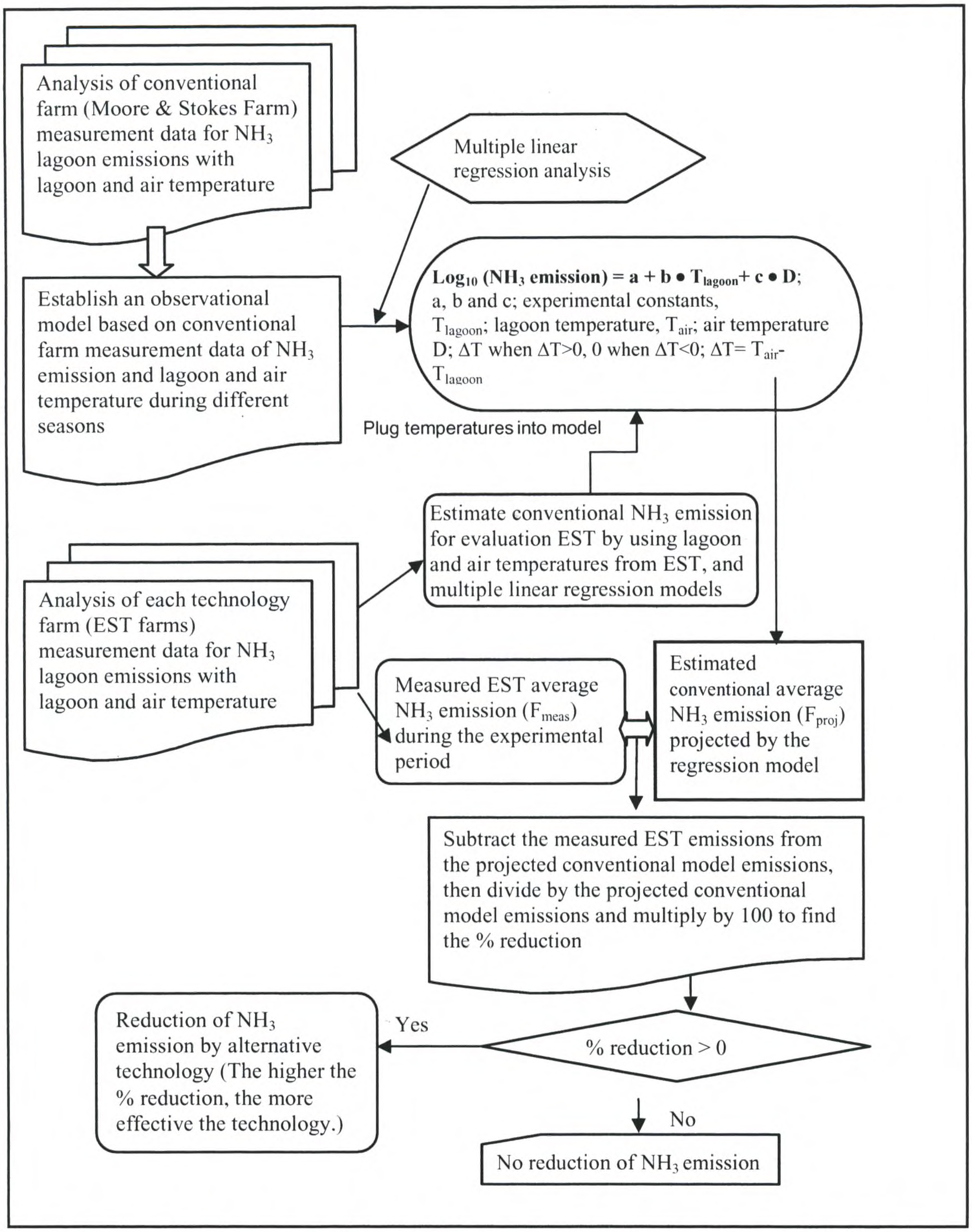

Figure 1. Algorithm flow chart for evaluation of EST emissions from water-holding structures.

Limitations:

Most of the candidate ESTs reported herein represent animal waste treatment systems that have undergone experimental development and performance testing. Some of the systems are continuing to be developed to improve efficiency of operation and reduce capital, operational and maintenance costs. Based on the work reported to date, most limitations are associated with operational feasibility and / or costs (see below). It is recommended that producers considering the candidate ESTs for implementation carefully assess available objective information related to the environmental performance, operational and economic feasibility of the referenced ESTs.

Cost:

Ten year annualized costs for the candidate ESTs are reported in Table 2.

Technology Summary:

The need for developing environmentally superior and sustainable solutions for managing the animal waste at commercial swine farms in eastern North Carolina has been recognized in recent years. During two-week long periods in two different seasons (warm and cold), NH_3 fluxes from water holding structures and NH_3 emissions from animal houses or barns were measured at eight potential EST sites: (1) Barham Farm – in-ground ambient temperature anaerobic digester/energy recovery/greenhouse vegetable production system; (2) BOC # 93 Farm -Up-flow biofiltration system - EKOKAN ; (3) Carrolls Farm- Aerobic Blanket System - ISSUES-ABS; (4) Corbett # 1 Farm - Solids separation/gasification for energy and ash recovery centralized system-BEST; (5) Corbett # 2 Farm – solid separation/ reciprocating water technology- ReCip; (6) Vestal Farm- Recycling of Nutrient, Energy and Water System-ISSUES-RENEW; (7) Goshen Ridge Farm (Solids Separation/nitrification-denitrification/soluble phosphorus removal/solids processing system (Super Soils);(8) Red Hill Farm ('Closed Loop' Swine Waste Treatment System). EST sites (7) and (8) did not contain anaerobic lagoons as part of their system. The ESTs were compared with similar measurements made at two conventional Lagoon and Spray Technology (LST) farms (Moore Farm and Stokes Farm). A flow-through dynamic chamber system and two sets of open-path FTIR spectrometers measured NH_3 fluxes continuously from water holding structures and emissions from housing units at the EST and conventional LST sites. In order to compare the emissions from the water-holding structures at the ESTs with those from the lagoons at the conventional sites under similar conditions, a statistical-observational model for lagoon NH_3 was used. A mass balance approach was used to quantify the emissions. All emissions were normalized by nitrogen excretion rates. Six of the eight ESTs that contained an anaerobic lagoon as part of the system did not substantially reduce ammonia emissions and therefore require additional technical modifications to be qualified as unconditional EST relative to ammonia emissions reductions. Two of the eight ESTs did not contain an anaerobic lagoon component. Both of these farms showed substantial reductions in NH_3 emissions from their water-holding structures. Under the conditions reported herein these two potential ESTs meet the criteria established for ammonia emissions as described for ESTs (Williams, 2004).

Table 1. Summary of NH_3 emissions from the EST farms and reduction during the experimental periods.

EST Farms	Sampling Periods	Emission Sources	Measured emission (F_{meas}) kg-N/wk/1000kg-lw	%E_{EST}	% E_{EST} (WHS + house)	EST avg. lagoon temp (°C)	EST avg. D (°C)	Conventional Lagoon emission (model/estimated) kg-N/wk/1000kg-lw (F_{proj})	% E_{CONV}	% E_{CONV} (lagoon + house)	% reduction
Barham	Apr. 2002	WHS	0.31	18.8	39.4	17.2	0.7	0.4	11.3	35.2	-11.9
		house	0.34	20.6				1.05	23.9 [†]		
	Nov. 2002	WHS	0.07	4.0	31.7	14.2	0.3	0.31	9.7	32.5	2.5
		house	0.49	27.7				0.89	22.8 [Δ]		
BOC # 93	Apr,03	WHS	0.23	8.2	28.4	18.5	0.7	0.46	14.3	37.1	23.5
		house	0.57	20.2				0.89	22.8 [Δ]		
	Jun,03	WHS	0.58	11.0	35.6	28.6	0.3	1.38	38.9	62.8	43.3
		house	1.29	24.6				1.05	23.9		
Carrolls farm	Mar-Apr,04	WHS	0.21	5.4	30.5	15.0	0.0	0.34	10.6	33.4	8.7
		house	0.98	25.1				0.89	22.8 [Δ]		
	Jun-Jul,04	WHS	0.23	5.6	33.4	29.1	0.0	1.50	42.2	66.1	49.5
		house	1.15	27.8				1.05	23.9		
Corbett # 1 Farm	Oct,03	WHS	0.33	5.6	8.3	21.8	0.2	0.69	19.4	29.4	71.8
		house	0.16	2.7				0.25	10.0 [♦]		
	Dec,03	WHS	0.12	5.1	5.4	9.3	0	0.19	5.9	15.9	66.0
		house	0.008	0.3				0.25	10.0 [♦]		
Corbett # 2 farm	Sep,03	WHS	0.35	11.0	14.8	14.9	1.6	0.28	8.7	18.7	20.9
		house	0.12	3.8				0.25	10.0 [♦]		
	Dec,03	WHS	0.81	18.0	28.9	24.1	1.0	0.78	22.0	32.0	9.7
		house	0.49	10.9				0.25	10.0 [♦]		
Vestal	Mar, 04	WHS	0.39	7.8	9.2	14.8	0.6	0.32	10.0	20.0	54.0
		house	0.07	1.4				0.25	10.0 [♦]		
	August,04	WHS	1.07	19.6	33.3	28.5	0.3	1.36	38.3	48.3	31.1
		house	0.75	13.7				0.25	10.0 [♦]		

[†] NH_3 emission measured from barns at tunnel (fan) ventilated conventional farm (Moore farm) during October 2002. [Δ] NH_3 emission measured from barns at tunnel (fan) ventilated conventional farm (Moore farm) during February 2003. [♦] NH_3 emission measured from barns at naturally ventilated conventional farm (Stokes farm) during January 2003. WHS = Water-holding structures

Table 2. Summary of total NH_3 emissions from the EST farms and % reduction during experimental periods.

EST Farms	Sampling Periods	Measured emission (F_{meas}) kg-N/wk/1000kg-lw	%E_{EST}	EST avg. lagoon temp (°C)	EST avg. D (°C)	Conventional lagoon emission (model/projected (F_{proj})) kg-N/wk/1000kg-lw	%E_{CONV}	% reduction
Goshen Ridge	Apr-May,03	0.02	0.6	17.2	0.7	0.40	11.3	94.7
	Feb-Mar ,04	0.004	0.1	14.2	0.3	0.31	9.7	99.0
Red Hill	Mar-Apr ,05	0.003	0.06	14.9	0.5	0.32	10.0	99.4
	July-Aug, 05	0.0006	0.01	31.6	0.0	1.95	54.9	99.98

Table 2. Ten year annualized costs for the candidate ESTs

EST Farms	10 year annualized cost ($ per 1000 lbs. steady state live weight per year)
Barham	$89
BOC # 93	$342
Carrolls	$95
Corbett # 1	$115 - $147
Corbett # 2	$143
Vestal	$126
Goshen Ridge	$400*
Red Hill	$137

For detail information see: (Williams, 2006. Table 8a, page 58)

* A Phase 2 generation of this technology has shown that the unit cost has been reduced to $300 or less. (see Williams, 2007)

Additional Resources:

Additional and detail information re materials and methods and cost information is available at http://www.cals.ncsu.edu/waste_mgt/

Acknowledgments:

Financial support provided by the North Carolina State University Animal and Poultry Waste Management Center (APWMC) is greatly appreciated. We sincerely acknowledge the help and support provided by Ms. Lynn Worley-Davis. We thank the technology PIs, farm owners, Cavanaugh & Associates, and Mr. Bundy Lane, C. Stokes, and P. Moore for their cooperation. We would also like to thank the various people who assisted in fieldwork including, Hilawe Semunegus, Wesley Stephens, and Srinath Krishan. We acknowledge the discussions and gracious help provided by Dr. John Fountain, Dr. Richard Patty, Dr. Ray Fornes, and Dr. Johnny Wynne of North Carolina State University. We thank Mark Barnes, Guillermo Rameriz, and Rachael Huie. We also thank Mr. Hoke Kimball, Mr. Mark Yarka, and Mr. Wade Daniels all of NC Division of Air Quality for their support. Thanks to Dr. Bruce Gay, US EPA; and Dr. Joette Steger, for their review of Project OPEN. Financial Support does not constitute an endorsement by the APWMC of the views expressed in the report, nor does mention of trade names of commercial or noncommercial products constitute endorsement or recommendation for use.

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As published in the proceedings of:
MITIGATING AIR EMISSIONS FROM ANIMAL FEEDING OPERATIONS CONFERENCE
Iowa State University Extension
Iowa State University College of Agriculture and Life Sciences
Conference Proceedings
Sponsored by:
NRI Air Quality Extension & Education
Iowa Farm Bureau Federation
Iowa Egg Council
Iowa Pork Industry Center
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Land Application

Effect on Residue Cover and Crop Yield of Manure Incorporation Equipment

H. M. Hanna, S. Mickelson, and S. Hoff
Iowa State University

Species: Swine, Dairy, Beef
Use Area: Land Application
Technology Category: Manure injection/incorporation
Air Mitigated Pollutants: Odor, Hydrogen Sulfide

Description:

Odor from livestock production faces increased public scrutiny. Manure spreading has been identified as producing more annoying odor to nearby residents than does the livestock facility itself (Noren, 1986; Janni et al., 2000). Some mixing of animal manure with soil reduces odor as compared with a broadcast application with no incorporation (Noren, 1986). In some cases, injection techniques may be able to reduce odor to a background level equivalent to odor from an unmanured soil surface. From a crop productivity standpoint, mixing manure nutrients with soil through injection or incorporation often results in greater yields and reduced nutrient losses in runoff and volatilization to the environment (Sawyer et al., 1991; Schmitt et al., 1995; Warnemuende et al., 1999).

Although manure incorporation has been widely adopted as a best management practice to control odor and minimize runoff and nutrient loss, incorporation also disturbs the soil and reduces residue cover. Maintenance of residue cover is important for control of soil erosion. In some locations a majority of acres need to maintain high surface residue cover for adequate erosion protection. Soil-disturbing operations typically reduce residue cover (Colvin et al., 1986), however different soil-engaging tools (e.g. discs, knives) on an implement can partially mitigate the amount of residue buried (Hanna et al., 1995). Incorporation systems reduce corn residue cover (Block et al., 1995). Fragile soybean residue cover is more difficult to maintain than is corn residue cover. Applying manure after soybeans and before corn to utilize manure nitrogen in a U.S. Midwestern row-crop system is a common practice.

Mitigation Mechanism:

Odor mitigation is accomplished by placement of manure below or within the soil surface. Hanna et al. (2000) measured effects of six different liquid application techniques with swine manure in both fall and spring applications on odor, corn and soybean residue cover, and crop yield in a corn-soybean crop rotation. Application treatments included injection with a: 1) 30-mm (1.25-in.)-wide narrow or no-till-style knife, 2) 50-mm (2-in.)-wide chisel or 3) 410-mm (16-in.)-wide sweep. Other application treatments included: 4) surface broadcast with immediate tandem-disk-harrow incorporation, 5) banding manure under residue but on the soil surface ("under residue"),and as a control comparison, 6) surface broadcast. The under residue treatment consisted of parting surface residue with a set of finger-wheel row cleaners, applying a band of manure on the soil surface, then using a set of finger-type closing wheels to pull surface residue with incidental amounts of soil back over the applied manure band. Manure was injected at a depth of 130 mm (5 in.) by the chisel, sweep, and narrow knife treatments. Soil was tilled to a shallow depth of 76 mm (3 in.) by the tandem disk harrow in order to minimize residue burial in the disk incorporation treatment. In the under residue treatment, manure was surface applied, but underneath crop residue with minimal disturbance of the soil surface.

As expected, a broadcast (only) application without incorporation left the most residue cover, but also produced odor levels that were often several times greater than most incorporation treatments (as measured by dilution of air to a threshold odor that was barely detectable). Hydrogen sulfide concentration in air above the broadcast treatment was greater than incorporated treatments. Incorporation effectively reduced odor (Fig. 1), and the narrow knife, under residue, and chisel methods minimized residue burial (Fig. 2) compared with other methods. When manure application was in fragile soybean residue, there was a greater range among treatments for the amount of residue cover left than with corn residue. Incorporation of manure before a subsequent crop generally increased corn yield beyond that of a broadcast application, particularly in a low-yield year, and did not affect soybean yield.

In addition to mitigating odor, when manure is injected or incorporated tillage is performed. Excess tillage is undesirable because of impacts on fuel use, soil conservation, and soil structure. Soil loosening from manure injection may be helpful, however, in poorly drained or cold soils as a form of strip tillage if manure is injected deep enough (e.g. 13 – 15 cm, (5 – 6 in.) below the surface) to avoid problems with seed germination and early plant growth.

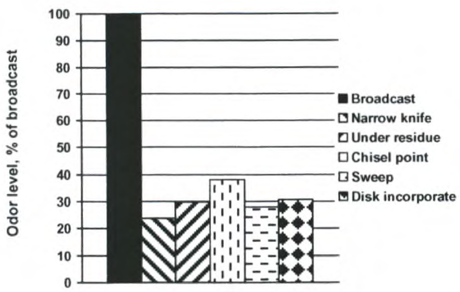

Figure 1. Odor level immediately after application in soybean residue.

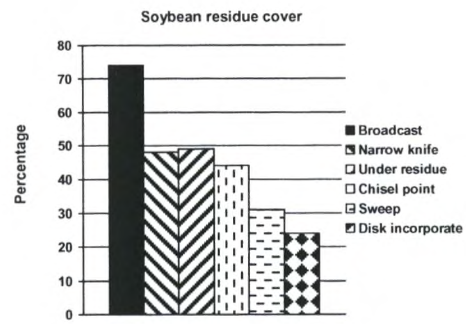

Figure 2. Residue cover after application in soybean residue

Applicability:

Injection of manure below the soil surface or incorporation of manure by mixing with surface soil should be utilized when odor is a concern. Concerns typically increase if neighbors or others not involved with the livestock operation will be subjected to odor during application and also with the application of swine manure. Most methods involving soil incorporation reduce odor levels by 20 to 90% from the odor level emitted after broadcast application.

The choice of a manure incorporation method in soybean residue is more critical to maintaining cover than in corn residue. Using a narrow-profile or "no-till" knife, or a single-disc opener tends to leave more residue than a disc-type system. When application is made in corn residue, there is less difference in the amount of residue cover remaining after treatments although they follow similar trends to those observed in soybean residue.

Limitations:

On land areas subject to erosion, serious consideration needs to be given to the type of injection or incorporation system used in order to limit burial of residue cover while still mitigating odor. In those cases where odor during application is not a concern and nutrient loss from surface placement can be tolerated, broadcast application minimizes residue cover destruction and required tractor power. Odor level reduces quickly with time and within a single day is often indistinguishable with odor from untreated soil.

Tractor power requirements increase with injection depth. Application with knives operating at 20 cm (8 in.) or greater depths may increase drawbar power requirement by 25%. Inject only as deep as required (e.g. 15 cm (6 in.)) to avoid problems with fertilizer burn on plant roots. If operating double-disc type systems where manure is incorporated in a dribble-band between discs using a shallow depth helps to maintain residue cover if manure can be placed between subsequent rows or at least 7 cm (3 in.) away from seed placement. Maintenance of injector styles is also a potential concern that should be evaluated. Single-disc type injectors tend to leave greater residue cover and minimize plant disturbance in pasture or hay, but have significant loading on disc bearings.

Cost:

Factors affecting costs include the initial cost of the application toolbar, annual usage rate, and increased tractor power requirement to pull the injection device. The following assumptions were made to calculate example costs for either a narrow ("no-till") knife injector or double-disc incorporation applicator toolbar for use by a large-volume custom or smaller-volume private applicator:

- Annual application volume: custom - 20 million gallons, private - 3 million gallons
- Equipment life: custom - 5 years, private - 15 years
- Additional tractor power: disc - 30 hp, knife - 60 hp

Costs of using a double-disc or narrow knife application toolbar are in the range of $0.001 and $0.002 per gallon, respectively, for the higher-volume custom applicator example. Costs are $0.0015 and 0.003 per gallon, respectively, for the lower-volume private applicator example. Costs of using additional tractor power are roughly one-third to one-half of total costs at the smaller annual application volume, but over three-fourths of costs at the higher application volume. Diesel fuel was valued at $3 per gallon. If the pass of a field tillage implement is eliminated (e.g., strip tillage) because of application, costs of injection or incorporation may be negated by savings in the cost of the tillage pass.

Implementation:

In addition to evaluating the need for odor control, field conditions should be carefully assessed for potential soil erosion from reduction of residue cover. Soybean residue is more fragile and subject to burial than corn or small grain residue. Reducing operating depth, or if possible using an injector style creating less soil and residue disturbance, tends to reduce loss of the soil-protecting residue cover. A narrow-profile knife may have greater application costs due to the knife-toolbar costs and power requirement, but may more consistently limit residue burial than double-disc system. A double-disc system may reduce costs and offer flexibility in heavy, corn residue but be too aggressive in soybean residue unless operating depth can be adjusted to a shallow level.

Consider depth of tillage for injection or incorporation of manure. If manure will be injected as a point source "in the row" (i.e., in a zone of subsequent seed placement), manure should be at least 7 cm (3 in.) below seed depth. If manure is applied away from the seed zone between rows or broadcast incorporated diffusely into the soil, a shallow tillage generally causes few problems with the subsequent crop. Even light mixing to gain manure exposure to the soil tends to cut odor significantly below that of a broadcast application.

Wet soil conditions are often observed during spring and sometimes during fall application season. Regardless of application choice, if at all possible when using heavy tanker axle loads, avoid application when soil is at or near field capacity to reduce the potential for subsequent soil compaction problems.

Technology Summary:

Injection or incorporation application treatments other than broadcast almost always reduce odor during and immediately after application. Although the amount of odor reduction among various injection and incorporation treatments may be similar, the level of surface residue cover reduction is different. For land areas where erosion is a concern operating an application system with reduced soil and residue disturbance should be strongly considered. Costs of using injection or incorporation equipment are on the order of $0.001 to $0.003 per gallon applied depending on the type of equipment and annual volume applied. Additional application costs for using injection or incorporation equipment even in the upper end of this range are typically no greater than the cost of a secondary tillage pass. The choice of injection or incorporation style should be strongly influenced by balancing the needs for odor control, residue cover maintenance, and fertilizer placement for the subsequent crop.

Additional Resources:

Manure and Tillage Management http://www.extension.iastate.edu/Publications/PM1901G.pdf

Acknowledgments:

Project support was provided in part by the National Pork Producers Council, Iowa Pork Producers Association, Top Air Manufacturing, Inc., and the Iowa Agricultural Experiment Station.

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As published in the proceedings of:
MITIGATING AIR EMISSIONS FROM ANIMAL FEEDING OPERATIONS CONFERENCE
Iowa State University Extension
Iowa State University College of Agriculture and Life Sciences
Conference Proceedings
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A Review of Manure Injection to Control Odor and Ammonia Emissions during the Land Application of Manure Slurries

R. Muhlbauer[1], J. Puck[2] and B. Puck[2], R. Burns[1]
Iowa State University[1], Puck Custom Enterprises[2]

Species:	Swine, Dairy, and Beef
Use Area:	Land Application
Technology Category:	Manure Injection
Air Mitigated Pollutants:	Ammonia, Odor

Description:

Manure slurry injection provides a significant reduction in odor and ammonia emissions from the land application of manure when compared to conventional surface broadcasting of manure. Release of odor and ammonia during land application can be reduced by more than 90% compared to conventional application methods (Ohio State University, 20[illegible]). Manure can be successfully injected in both conventional tillage and no-till systems with currently available equipment. Current equipment options and costs are presented in this paper for both drag-hose and tanker systems. The positive and negative aspects of each system type will be discussed. Additionally the cost to have manure injected by professional commercial applicators will also be discussed.

Research by Hanna et al., (2000) compared the odor and ammonia volatilization mitigation capabilities of various types of manure injection techniques to slurry that was surface applied (broadcasted). Air samples were taken immediately after application, the day after, and five days after application. The samples were analyzed using a dynamic olfactometer and a four-member panel. Odor level was determined in odor units, or the average number of dilutions required to obtain undetectable odor (the threshold odor level). Ammonia concentration was measured with a Sensidyne ammonia tube (SKC, Inc., Eighty-four, Pennsylvania). Odor and ammonia tests were run for both fall and spring application. Ammonia was below the detection limit (0.2 ppm) for all but two (measured at 0.6 and 1.3 ppm) of the 72 samples taken. Table 1 contains some of the odor data presented by Hanna.

Table 1. Odor* measured from application of swine slurry on soybean residue (Hanna et. al. 2000)

	Fall Application			Spring Application	
Application	At Application	One Day After	Five Days After	At Application	One Day After
Broadcast	807	876	63	140	40
Narrow Knife Injection	185	52	43	61	44
Sweep Injection	94	60	43	35	16
Chisel Injection	256	113	43	33	43

*Odor units are the number of clean air dilutions required to reach the threshold odor level for a panel of four observers.

This research shows broadcasting manure requires approximately 4 to 5 times the fresh air dilutions required to reach the threshold level compared to the number of dilutions required for injected manure, indicating the large odor reduction provided by injection compared to broadcasting. In a different study odor intensity from broadcasting at 400 meters downwind was found to be similar to that of injection at only 50 meters (Berglund and Hall, 1987).

Mitigation Mechanism:

A variety of tools are available to inject slurry but all perform similarly. The tool (a narrow knife, a sweep, chisel plow or chisel ripper) slices through the soil to create a sub-surface cavity approximately 13-23 cm (5-9 inches) deep (Puck, 2008). The slurry is injected through tubes directly into the cavity behind the tool. This provides immediate mixing of slurry and soil as well minimizing exposed slurry and residue cover disturbance. By minimizing slurry exposure to air, odor is reduced significantly and ammonia volatilization is mostly avoided.

Applicability:

Injection application can be used with any slurry or liquid type manure which is greater than 85% and 90% moisture content for swine and dairy waste respectively (AMWFH, 2007). Injection is used extensively for swine slurry and liquid dairy manure but can also be used to apply captured beef feedlot runoff. Additionally, most injection tools leave enough crop residue to accommodate no-till cropping schemes. Hanna et al. (2000) found that injection tools left soybean crop residues 75-85% intact.

Limitations:

Compared to conventional broadcast of manure, injection has a few limitations. Injection generally requires as much as 30% more tractor horsepower than broadcast because of the added weight and drag of the injection tools in the soil, especially in hilly terrain (Puck, 2008). Injection may not be desirable in forage or pasture/sod fields where the producer does not with to disturb soil. In this case, broadcasting may be required. Injection tools and the hydraulic systems required to lift the tools from the ground will wear requiring more maintenance than a broadcast system.

Cost:

Generally, injection is more costly than broadcast application. Injection requires more tractor horsepower and more equipment (injection tool bars). Because tool bars are pulled through the soil, wear and maintenance is greater with injection systems. Tables 2 and 3 give the cost of commercial drag hose slurry injection and broadcast respectively in $/gal and $/L. Figures 1 and 2 show the cost of commercial drag hose slurry injection and broadcast respectively in $/acre with increasing transfer distance. Cost increases as application rate decreases and as distance from the manure storage site increases. Puck Custom Enterprises (PCE) applies a mileage charge of $.001/gal/mile for every mile over one from the manure storage site (Puck, 2008). The increase in cost as application rate decreases is due to wear on the application equipment. At lower application rates, field speed is increased causing wear (and eventually maintenance) on the equipment to increase.

Table 2. Commercial slurry injection cost for drag hose application one mile from the site (Puck, 2008).

Gallons/acre	Inch-acres	Liters/hectare	$/gal (1 mile)	$/L (1 mile)
3000	0.11	28037	$ 0.019	$ 0.0050
4000	0.15	37383	$ 0.017	$ 0.0044
4750	0.17	44392	$ 0.015	$ 0.0038
5500	0.20	51401	$ 0.014	$ 0.0037
7000	0.26	65420	$ 0.014	$ 0.0036
9000	0.33	84111	$ 0.013	$ 0.0034
12000	0.44	112148	$ 0.012	$ 0.0032

Table 3. Commercial slurry broadcast cost for drag hose application one mile from the site (Puck, 2008).

Gallons/acre	Inch-acres	Liters/hectare	$/gal (1 mile)	$/L (1 mile)
3000	0.11	28037	$ 0.010	$ 0.0026
4000	0.15	37383	$ 0.010	$ 0.0026
4750	0.17	44392	$ 0.010	$ 0.0026
5500	0.20	51401	$ 0.010	$ 0.0026
6000	0.22	56074	$ 0.0085	$ 0.0022
9000	0.33	84111	$ 0.0085	$ 0.0022
12000	0.44	112148	$ 0.0085	$ 0.0022

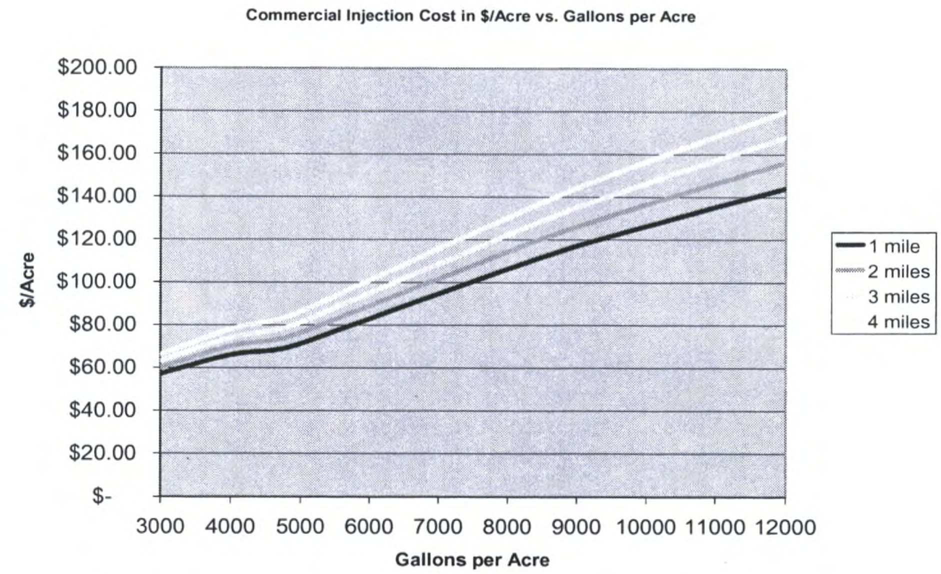

Figure 1. Commercial injection cost for drag hose application (Puck, 2008).

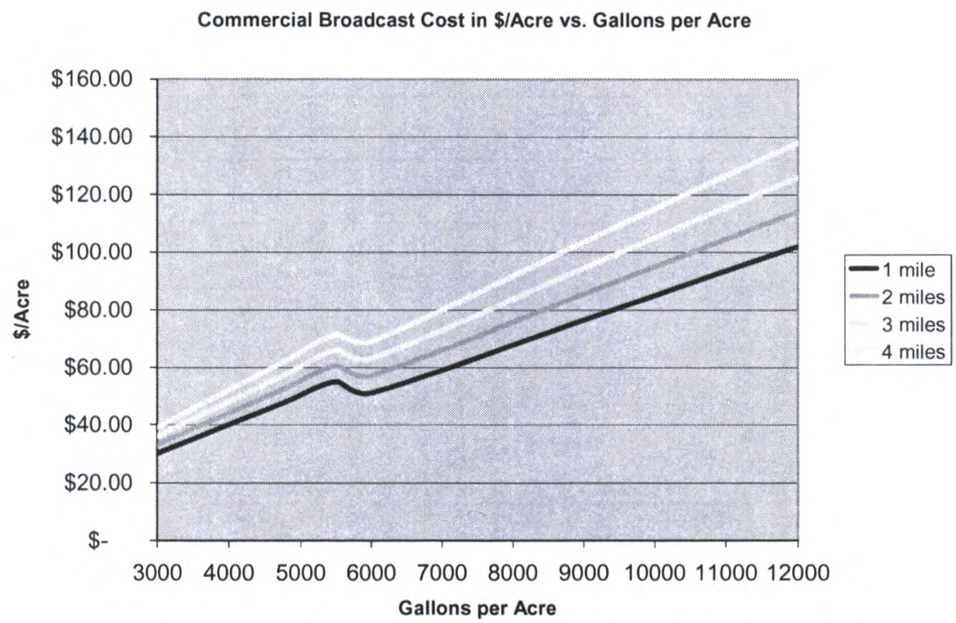

Figure 2. Commercial broadcast cost for drag hose application (Puck, 2008).

Tables 3 and 4 give ownership and maintenance cost data for tanker wagon and drag hose injection systems respectively. In Tables 5 and 6, the operational cost is compared to the cost of commercial application for wagon and drag hose injection systems respectively. The ownership and operational cost for both systems is represented graphically in Figures 3 and 4. It should be noted that the estimates include the purchase of tractors required to operate the systems. Costs will we less if the producer already owns adequate tractor power but the maintenance and operation costs will remain because they are specific to the systems. Additionally, if the producer already owns a tanker wagon and wishes to retrofit it with an injector bar the cost will be reduced. The cost for wagons in Table 3 includes the wagon and injector bar. Wagons can be retrofitted with a 6.7m (22 ft), five tool injection tool bar for approximately $12,000 (Puck, 2008).

Table 3. Tanker wagon injection system ownership and maintenance cost (Puck, 2008)*.

	Capital (1 wagon)**	Capital (2 wagons)	Capital (3 wagons)	Maintenance (1 wagon, $/year)***	Maintenance (2 wagons, $/year)	Maintenance (3 wagons, $/year)
Used 220 HP tractor (wagon)	$50,000	$100,000	$150,000	$4,000	$8,000	$12,000
Used 100 HP tractor (pump/agitator)	$15,000	$15,000	$15,000	$1,200	$1,200	$1,200
Load stand	$500	$500	$500	$40	$40	$40
4800 gallon tanker with injection tool bar	$41,500	$83,000	$124,500	$3,320	$6,640	$9,960
Agitator pump	$12,000	$12,000	$12,000	$960	$960	$960
Total	$119,000	$210,500	$302,000	$9,520	$16,840	$24,160

* Values are estimates from Puck Custom Enterprises, a commercial manure application business utilizing wagon and drag hose systems.
** Values are based on estimates for new equipment unless otherwise stated.
*** Yearly average for 5 years of operation.

Table 4. Drag hose injection system ownership and maintenance cost, (Puck, 2008)*

	Capital cost**		Maintenance cost/year***	
Boom Truck (with feeder pump and high pressure pump)	$100,000		$8,000	
Hose Cart	$19,950		$1,596	
Used 240 HP MFWD tractor (tool bar)	$95,000		$7,600	
Used 130 HP tractor (hose cart)	$25,000		$2,000	
Used 100 HP tractor (agitation pump)	$10,000		$800	
22', 7 knife, injection tool bar with flowmeter	$31,000		$2,480	
ATV (for checking hose)	$4,000		$320	
1/4 mile 5" drag Hose	$12,210		$977	
1 mile 6" transfer hose	$42,240		$3,379	
Agitator pump	$12,000		$960	
Total	$351,400		$28,112	

* Values are estimates from Puck Custom Enterprises, a commercial manure application business utilizing wagon and drag hose systems.
** Values are based on estimates for new equipment unless otherwise stated.
*** Yearly average for 5 years of operation

Table 5. Wagon injection system operation cost compared to commercial application cost (Puck, 2008)*.

Gallons applied per year (millions)	Maintenance ($/year)**	5 year amoritization capital cost, 6.5% ($/year)	Fuel cost, $3.00/gal ($/year)	Labor ($/year)***	Insurance ($/year)	Total ownership cost ($/year)****	Commercial application cost, $.0135/gal ($/year)*****
1	$9,520	$28,636	$3,000	$1,953	$6,500	$49,609	$13,500
4	$9,520	$28,636	$12,000	$7,813	$6,500	$64,468	$54,000
8	$16,840	$50,654	$24,000	$15,625	$6,500	$113,619	$108,000
11	$16,840	$50,654	$33,000	$21,484	$6,500	$128,478	$148,500
15	$24,160	$72,672	$45,000	$29,297	$6,500	$177,629	$202,500
20	$24,160	$72,672	$60,000	$39,063	$6,500	$202,394	$270,000

* Values are estimates from Puck Custom Enterprises, a commercial manure application business utilizing wagon and drag hose systems.
** Yearly average for 5 years of operation.
*** Based on $15/hour/worker, 1 laborer per wagon, 2 loads/hour/wagon, plus 25% for equipment transport and downtime labor.
**** It is assumed 1 wagon is used for less than 8 million gallons, 2 wagons for 8 -15 million gallons, and 3 wagons for over 15 million gallons.
***** Average (application rate, transport distance) commercial application cost of drag hose injection.

Table 6. Drag hose injection operation cost compared to commercial application cost, (Puck, 2008)*.

Gallons applied per year (millions)	Maintenance ($/year)**	5 year amoritization capital cost, 6.5% ($/year)	Fuel cost ($3.00/gal, $/year)	Labor*** ($/year)	Insurance ($/year)	Total ownership cost ($/year)	Commercial application cost, $.0135/gal ($/year)****
1	$28,112	$84,559	$2,250	$750	$12,500	$128,171	$13,500
2.5	$28,112	$84,559	$5,625	$1,875	$12,500	$132,671	$33,750
5	$28,112	$84,559	$11,250	$3,750	$12,500	$140,171	$67,500
10	$28,112	$84,559	$22,500	$7,500	$12,500	$155,171	$135,000
15	$28,112	$84,559	$33,750	$11,250	$12,500	$170,171	$202,500
20	$28,112	$84,559	$45,000	$15,000	$12,500	$185,171	$270,000
25	$28,112	$84,559	$56,250	$18,750	$12,500	$200,171	$337,500

* Values are estimates from Puck Custom Enterprises, a commercial manure application business utilizing wagon and drag hose systems.
** Yearly average for 5 years of operation
*** Based on 2 laborers, $15/hour/laborer, 40,000 gallons/hour efficiency (60,000 gallons/hour minus 33% for set-up, transportation, and maintenance).
**** Average (application rate, transport distance) commercial application cost of drag hose injection.

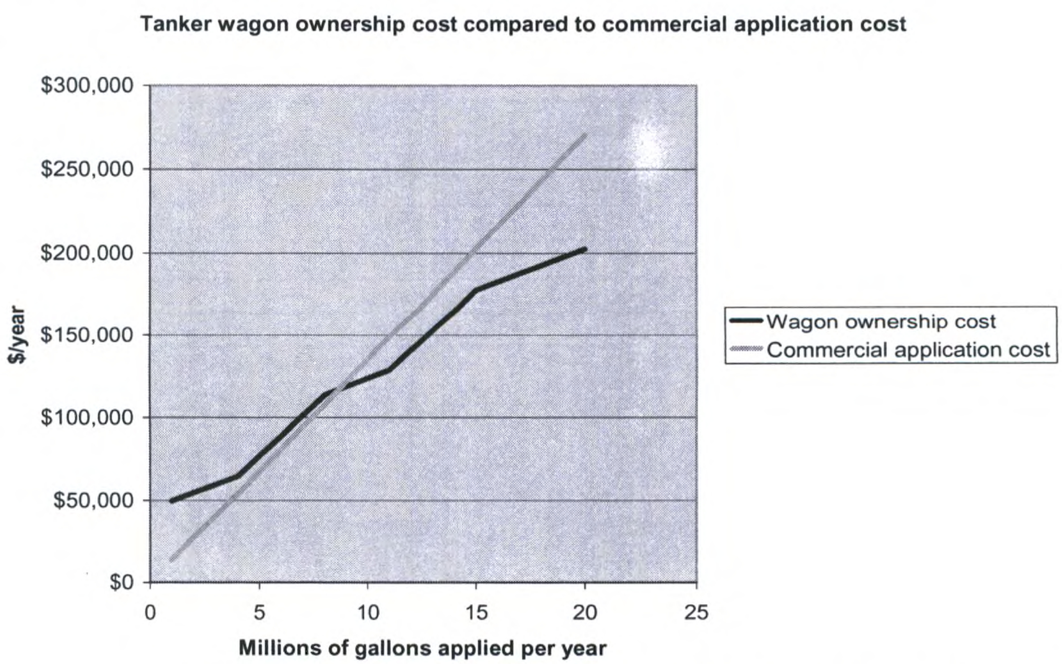

Figure 3. Tanker wagon injection system ownership and operation cost compared to commercial application cost (Puck, 2008).

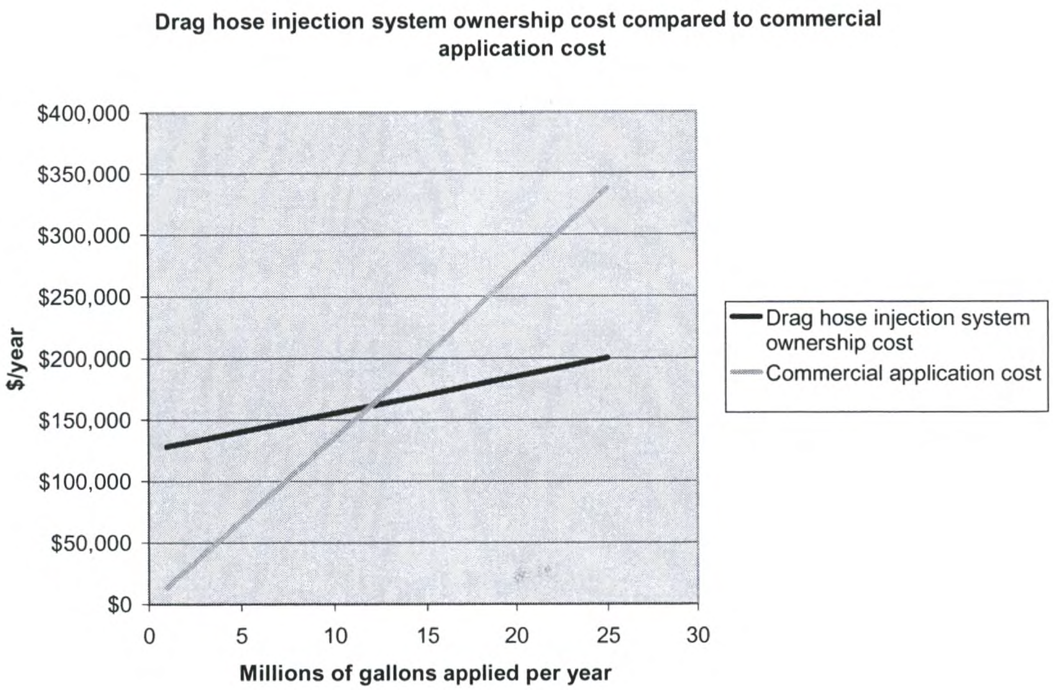

Figure 4. Drag hose injection system ownership and operation cost compared to commercial application.

Implementation:

Injection equipment can be purchased from many different vendors. If a producer currently uses a tanker wagon to broadcast slurry, most wagons can be retrofitted with an injection toolbar. If large amounts of slurry are to be applied (greater than 5 million gallons) a drag hose injection system may offer the best performance. It should be noted that with drag hose injections systems the slurry flow is continuous and that surface spillage will occur on end rows while turning around. The spillage should be incorporated to avoid odor and ammonia volatilization associated with surface application.

Additional Resources:

More information can be found through Puck Custom Enterprises (PCE).

Puck Custom Enterprises
1130 100th street
Manning, IA 51455
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www.puckenterprises.com

Acknowledgments:

The majority of manure handling equipment information was provided by Puck Custom Enterprises (PCE). PCE has been a commercial application business in western Iowa for over 27 years. Currently, PCE owns and operates several drag hose systems as well as tanker wagons to apply over 100 million gallons of swine, dairy, and beef feedlot slurry per year.

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As published in the proceedings of:
MITIGATING AIR EMISSIONS FROM ANIMAL FEEDING OPERATIONS CONFERENCE
Iowa State University Extension
Iowa State University College of Agriculture and Life Sciences
Conference Proceedings
Sponsored by:
NRI Air Quality Extension & Education
U.S. Pork Center of Excellence
Iowa Farm Bureau Federation
Iowa Egg Council
Iowa Pork Industry Center
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Invited Presentations

AGRICULTURE AND FEDERAL AIR QUALITY POLICY OUTLOOK

T. R. Hebert
Senior Vice President
Ogilvy Government Relations

I have been asked to speak to you on the outlook for federal air quality regulatory policies applicable to livestock and poultry producers. The good news about this talk is that I have a lot of policy "data" to deal with. The bad news is that this policy "data" indicates that there are multiple possible and significantly divergent paths that these federal policies could go down.

Despite all the policy uncertainty we face, there is one thing I can say for certain. Livestock and poultry producers will most definitely need effective, sound, practical and economical air emissions mitigation practices. For that reason alone, I applaud ISU for holding this important conference. And I also want to thank all of you, on behalf of agriculture, for your efforts now and in the future to develop economical emission mitigation tools. Please keep it up, and thanks to ISU for bringing attention to where we are now in developing these tools and helping us focus on where we need to go.

Currently, as you all know, livestock and poultry producer groups are actively engaged in the National Air Emissions Monitoring Study (NAEMS), an effort that is currently scheduled to be completed at the end of 2009. At the point of NAEMS completion, EPA will develop air emission factors or coefficients for use in either the federal Superfund air emissions program or possibly in some instances by states as part of the development and implementation of their State Implementation Plans (or SIPs) under the Clean Air Act (CAA). I also fully expect that the other non-NAEMS emission factor research that will have been done by this point for the broiler and turkey industries will also be used by EPA in their emission factor development efforts.

In terms of federal policy outlook, we should all expect that starting sometime in 2010 and possibly finishing in 2011; EPA will carry out an emission factor development process from the NAEMS and related data. That process is supposed to be open to substantive and extensive input and comment from the scientific community and other members of the public, and there is no reason at this point in time to expect that not to happen. I expect that there are several of you in this audience who could make a significant and meaningful contribution to how EPA turns the NAEMS and other data sets into emission factors, and I encourage you to take advantage of that opportunity if you can.

In addition to the post-NAEMS emission factor development work, there are five primary policy/regulatory issues or issue areas that I am going to be paying particular attention to over the next several months to a few years. These five issues or issue areas are:

1. EPA's possible final rulemaking dealing with excluding livestock and poultry producers from the air emission reporting requirements under CERCLA/EPCRA;
2. On-going regulation of livestock and poultry operations under the Clean Air Act in California in ozone non-attainment areas;
3. The implications for ammonia management from the CAA rulemaking completed in 2007 governing the development of SIPs for fine particulate matter (PM2.5);
4. The potential establishment of a secondary National Ambient Air Quality Standard (NAAQS) for all reactive forms of nitrogen (N); and lastly
5. Climate change legislation, with important possible implications for methane, and nitrous oxide emissions and management from livestock and poultry facilities.

These are discussed briefly below.

CERCLA/EPCRA RULEMAKING

EPA issued a proposal at the end of 2007 to exclude air emissions from poultry and livestock houses from the emergency reporting requirements of CERCLA/EPCRA – the federal Superfund laws. Some are treating this proposed rule as having a big environmental impact, but in my view this is hardly the case. That is in part apparent from the fact that this rulemaking is only tangentially relevant to the critical subject matter of this conference. These CERCLA/EPCRA requirements in question simply require reporting by these operations, and no mitigation of emissions is expected or called for. And nothing in EPA's proposal diminishes EPA's ability to require clean up or remedial actions on the part of these livestock operations, should EPA determine that is needed under CERCLA/EPCRA. Still, I offer these observations about this provision as it is very much in the news, deals with air emissions, and in many ways will be part of the tone or context to come in DC for consideration of what comes next in air emissions policy.

I am of the view that the chances are good that EPA will adopt this proposal in a final rulemaking before the end of 2008. It will be controversial as some key Democrats in Congress have called upon EPA not to adopt this in a final rule. But from EPA's perspective it makes absolute good sense. Reporting these emissions serves no practical purpose for the emergency response agencies, and in fact appears to represent costs and distractions from their important work that are worth avoiding. It certainly raises all kinds of questions of liability for CAFOs unrelated to actual environmental impacts or emergency response.

But the bottom line is that whatever you might think about these operations, the ammonia and hydrogen sulfide produced from the animals' manure does not represent an **emergency** health threat to the general public outside of the animal houses. As such, there will never be a local or state emergency response needed or called for as a result of these emissions. (Please see the comments submitted by the major livestock and poultry groups on this EPA proposed rule for a discussion of the literature on the likely concentration levels of these substances in the airspace outside these animal houses relative to the best known ambient air public health standards.) Furthermore, there is no mystery as to where these livestock and poultry operations are located, and no mystery as to the chemical content of these emissions from manure. CERCLA/EPCRA reporting of ammonia and hydrogen sulfide does not add in any meaningful way to this knowledge base for the general public or anyone else for that matter.

This is at its core a common sense proposal and I expect and hope that EPA will follow through on its adoption. But if they do so, it will be controversial in Congress, and if the next Administration is a Democratic one, there will be calls to rescind the rule. I am not convinced that will actually be done in that event. In 2009 and beyond there will be a great deal of more pressing work than the reporting of extraneous agricultural information to the Coast Guard, and a common sense position like this one could very well ultimately prevail. It is ironic that the CERCLA/EPCRA threat in the late 1990's of enforcing against CAFOs, and actual enforcement actions themselves, for failure to report these emissions has in part been the driving force behind the NAEMS work. The emissions factors generated as a result of NAEMS will add to our knowledge base and be important perhaps to environmental improvement efforts under the CAA, but there never was anything significant to be gained for the environment from the CERCLA/EPCRA reporting requirements.

CLEAN AIR ACT IMPLEMENTATION IN CALIFORNIA

Legislation adopted in 2003 in California ended an agricultural exemption from CAA permitting requirements for both major and minor sources. In addition to the general particulate matter requirements, Confined Animal Facilities (CAFs) would be required to install and use practices to reduce emissions of volatile organic compounds (VOCs), as these are considered precursors to ozone formation in the state's ozone nonattainment areas. These changes provided for enforceable rules and regulations applicable to agriculture and CAFs in particular. In the San Joaquin Valley, up to 1,100 CAFs were thought to be subject to the requirements to adopt Best Available Retrofit Control Technology (BARCT), and about 350 large CAFs subject to the permitting requirements. These requirements are quite detailed, as shown revealed in the checklist that the San Joaquin Air Pollution Control District provides to dairy operations to help them comply with these requirements. The checklist is not the actual permit, and the permit would be the document that specifies the final list of practices to be implemented for a particular operation.

Of course, the circumstances in California with respect to ozone non-attainment areas and agriculture's presence in these areas will not necessarily be the case in other states and regions. The CAA is sensible in that regard. It truly is supposed to be local air quality conditions that drive regulatory requirements, and where the conditions do not warrant it, regulatory requirements should not be imposed. But we can be confident that state air regulatory agencies across the US are watching the California experience with regulating the emissions from these agricultural operations, and will be seeking to learn from it for possible use in their programs. I encourage this community to pay attention as well to the practices being required and their utility in generating actual air quality benefits.

AMMONIA, PM FINE AND SIPS

In 2007, EPA issued a final rule governing how states are to address their responsibilities to develop State Implementation Plans (SIPs) for non-attainment areas under the 1997 PM2.5 NAAQS. Under that final rule, states are required to evaluate direct PM2.5 and SO2 for control measures in each area. Sources of NOx must be evaluated for control measures in each area as well, unless the state and EPA provide a technical demonstration showing that NOx emissions from sources in the State do not significantly contribute to PM2.5 concentrations in a specific area. Sources of VOC are not required to be evaluated for control measures in each area, unless the state or EPA provides a technical demonstration showing that VOC emissions from sources in the State significantly contribute to PM2.5 concentrations in a specific area.

Of particular interest to agriculture and the subject matter of this conference, under this SIP rulemaking EPA did **not** require sources of ammonia to be evaluated for control measures in each area, unless the state or EPA provides a technical demonstration showing that ammonia emissions from sources in the state significantly contribute to PM2.5 concentrations in a specific area.

Given the levels of ammonia known to be emitted from many of our livestock facilities and likely association with certain non-attainment areas, I would not be surprised if some states do not actively explore the linkages between our ammonia emissions and PM2.5 non-attainment. I would expect to see state proposals before EPA that certain SIP's include emission reduction measures from our facilities in some locations.

SECONDARY NAAQS FOR TOTAL REACTIVE NITROGEN (N)

This issue, along with the climate change issues discussed below, will likely be the subject of considerable scientific and policy discussion in years to come. It is part of a broader discussion happening in the environmental science community about the growing and pervasive presence of biologically and ecologically active forms of N, and developing calls for policies that diminish reactive N emissions into the environment. As agricultural scientists you understand just how enormous a challenge such a policy goal would represent. Human food production since the inception of agrarian societies has always depended on the addition of N to support crop and livestock systems. N is essential for crop and livestock production, and it is its very properties of mobility and reactivity that make it some biologically important to plant growth, and it is these same properties that create the associated environmental challenges. This is not going to change and there is always going to be large quantities of reactive N in our food production systems.

Relative to the subject matter of this conference, EPA's Integrated Reactive Nitrogen Committee, part of EPA's Science Advisory Board, has recommended that EPA establish a **secondary** NAAQS under the CAA for total reactive nitrogen, including ammonia, treating these as a criteria pollutant. A "secondary" standard is not a human health or "primary" NAAQS. A secondary standard focuses exclusively on welfare issues like effects on the natural environment, independent of any specific human health considerations. EPA faces enormous procedural and legal challenges in creating a stand-alone secondary reactive N standard.

If the next Administration is a Democratic one, I would not at all be surprised to see them try to create this secondary standard over the course of the next eight years. And once EPA initiates such a process, whether or not it succeeds, you can guarantee that the level of scrutiny that livestock and poultry ammonia air emissions will receive will increase by at least an order of magnitude, and a visible increase in the demand for affordable and effective ammonia emissions reductions practices. And if EPA succeeds in setting such a standard, the regulatory driven demand for such practices will be enormous. Either way, your help to develop such tools and methods will be needed.

CLIMATE CHANGE AND CH_4 AND N_2O

There is a widespread assumption in Washington DC, that in 2009 or 2010 Congress will pass and the President will sign climate change legislation with far reaching and implications fundamental to the operations of our economy. Whether one bill or several, and whether a Republican or Democrat sits in the White House, the thinking goes that such legislation is coming. While I share the view that legislative action is coming and that something will be signed into law, I am less certain about how far reaching and substantive that legislation will be.

There is dispute about the economic costs of intelligent green house gas (GHG) emission reductions, and some contend that over several decades it will only reduce economic growth a few percentage points relative to what would have occurred otherwise. I do not share that view and do not see how any aggressive and significant GHG reduction effort can do anything but impose serious and painful costs on our economy. If my view is correct, then as Congress and the President consider such legislation during what appears to be a time of a near (if not actual) economic recession, I imagine final legislation that is long on process and research and efforts, and less on enforceable reductions in GHG emissions. From agriculture's perspective, the critical issue is that even in this lighter, less aggressive form, the final climate change provisions will include significant incentives for agriculture to provide GHG offsets or credits. This should be on considerable interest to your research programs.

There is some question about how livestock agriculture will be treated in such legislation. Currently, the Lieberman-Warner climate change bill does not require GHG reductions from any part of production agriculture – crop, livestock or poultry. Instead, agriculture is being called upon to provide GHG reduction credits that the regulated industries (utilities and mobile sources) can use. These credits can be generated through carbon sequestration on crop land or the capture and destruction of methane or nitrous oxides that would otherwise be emitted as part of manure management practices. I do not ever expect crop agriculture to be a regulated industry under GHG legislation, but there are those that discuss requiring mandatory GHG reductions from livestock producers. I do not see that happening. All of agriculture, according to EPA, accounts for about 6.5% of the country's **total** GHG emissions. Given this fact and the obstacles in Congress to passing climate change legislation, I would expect practical members of Congress to find a way to have all of agriculture be an ally in support of legislation, and not a regulated entity seeking to stop it or diminish its effect.

The bottom line in my view is that whether we have legislation with aggressive or less aggressive, enforceable GHG reduction requirements, the legislation will look for ways to promote GHG emission reductions where significant and cost effective gains are possible. This is certainly the case for agriculture and livestock and poultry agriculture will have significant opportunities to generate revenue through the capture, use or destruction of methane and nitrous oxides. As such, the challenge is there for this research community represented by you in the audience to help generate the practices and techniques that make such GHG reductions more cost effective or in some cases even possible. There are still a large number of practical or expensive considerations with the capture of methane from manure. We need those costs reduced and challenges solved. I have no idea even where to begin on N2O or how much of a challenge this represents. But N2O is 300 times more potent a GHG than CO2, and so significant opportunities exist if we can capture and destroy this, or render it less potent a GHG.

SUMMARY

I have always been of the view that it is the CAA that has the most significant, on the ground implications for livestock and poultry agriculture. Clearly, there are other concerns and opportunities, like those associated with GHG as discussed above. But the CAA is the most likely source of actual and relatively large dollar outlays for the adoption of emission reduction technology and practices. In terms of federal law, it will be the CAA, much more so than CERCLA/EPCRA that will drive the demand by farmers for the technologies and practices that are the subject of this conference.

We do have some time, though, and I hope we will use it wisely to develop and refine economical and effective emission reduction practices. We have time because policy makers will naturally want to see how NAEMS and the resulting emissions factors turn out and what we can learn from the NAEMS results in general. We also have time because the CAA is an extremely complicated statute, requiring famously detailed and Byzantine procedures for the development and implementation of policy. At multiple stages of this process the opportunities for lawsuits abound, increasing by an order of magnitude or two the uncertainties about what the statute will mean in practice at specific locations and at specific times across the country. And as in many similar instances involving aggressive and detailed federal law that utilizes state authorities and programs to put it into effect, there can be a wide divergence between what the statute can in theory make happen or require, the actual resources and will to make that theory a reality, and therefore what really does in fact occur. And the fact that all of livestock and poultry agriculture would be affected, as opposed to one sector (like was the initial case in the late 1990's with swine and water quality concerns) means that all of livestock agriculture will be engaged in this policy making process. That will likely make the process go more slowly and more carefully.

But we should make no mistake. Air quality considerations and practical, cost effective measures to mitigate our air emissions, are going to critically important to the future of livestock and poultry agriculture in the US. And for the foreseeable future, US livestock and poultry agriculture will be critical to the future of US feed grain and oilseed agriculture. Therefore, your work is more important than ever. Thank you very much for all that you have done to this point and please redouble your efforts to help agriculture deal with this important and critical challenge of improving their environmental performance through reductions in their air emissions.

US ANIMAL FEEDING OPERATIONS AIR EMISSIONS MITIGATION STATE OF SCIENCE

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Abstract. Animal feeding operations present unique challenges to engineers and scientists seeking to develop suitable and effective mitigation strategies. This presentation addresses the current state of the science for abatement technologies used in the U.S. as well as available technologies not currently being implemented. The presentation will also discuss issues of practicality and economic feasibility that may currently be limiting the adoption of some mitigation approaches.
Keywords. Agriculture, Air Quality, Poultry, Manure Management, Treatment

INTRODUCTION

Animal Feeding Operations (AFOs), and especially Concentrated AFOs (CAFOs), can present unique challenges to the environment. AFOs have arisen owing to the economy of scale they can provide. Transportation, animal housing, feed, fuel, water and veterinary inputs can be managed at lower costs. Marketed product quality and quantity can be controlled for optimal profitability. Livestock and poultry manure management is part of the design of AFO systems, and the scale of these operations means that properly engineered treatment and storage systems are more likely to be employed. However the scale of these systems also means that they can be significant sources of atmospheric and watershed contamination; and while agricultural water quality has been a focus for several decades, a focus on agricultural air quality is more recent.

The concentration of animal units, whether on a farm, a locale, or a region, can present substantial environmental challenge. However, this concentration of animal units is also an opportunity for large-scale and efficient management and mitigation of environmental impacts. Despite this opportunity, air quality and water quality together represent the substantial majority of complaints and regulatory challenges to AFOs. Research and development to mitigate the impact of AFOs on agricultural air quality in the U.S. has increased greatly in recent years, in part due to increased regulatory scrutiny of AFOs, litigation regarding public nuisance and interpretation of applicability of community right-to-know laws and an increase in funding under the USDA National Research Initiative's Agricultural Air Quality Program (and previously, under the USDA Initiative for the Future of Agricultural and Food Systems). Implementing best management practices (BMPs), and developing new BMPs and best-available technologies, has been a focus for the USDA NRCS under the Conservation Innovation Grants and EQIP programs and many Land-Grant University projects. Funding has been applied to the broad arena of agricultural air quality, i.e. cropping systems, tillage, forestry and AFOs. With the recent acceleration in efforts to address air quality and mitigation of US AFOs, it is appropriate to examine the current state of the science.

STATE OF THE SCIENCE – US AFOs

What is the current state of the science with respect to mitigating US AFO air emissions? A review of recent and current funded air quality projects (USDA, 2008) and recent air quality conferences shows a wealth of new material and accelerated activities. Broadly speaking, the following list of focus areas can be noted:

- Baseline emissions quantification, including improved measurement systems and sampling protocols.
- Model development and validation.
- Mitigation efforts.

BASELINE EMISSIONS QUANTIFICATION

Recent baseline emission data

A wealth of recently completed and current projects is becoming published in the scientific literature. Topical areas include: particulate matter properties, emissions, and composition; gaseous emissions including ammonia as a particulate pre-cursor, carbon dioxide, methane, hydrogen sulfide, volatile organic compounds, sulfur oxides and nitrous oxide; odor properties, composition, and emissions. Specialty conferences, technical committees, multi-state Hatch projects and other research groups are collecting and publishing this information.

By way of example, Tables 1 and 2 list recently acquired ammonia emission data for US broiler chicken housing (from Burns et al 2007a, Table 1) and a comparison to European literature (from Wheeler et al., 2006). By contrast, six years ago there were no published US ammonia emissions data. Comparison of US baseline data to European data show generally lower values in the latter owing to new litter after each flock, smaller mature bird weights, and bird age at emissions sampling. The earlier literature also lacked any statement of uncertainty in measurements and details regarding production practices in the houses that were sampled. This is a common difficulty in assessing much of the recent literature on baseline emissions.

Table 1. Comparison of ammonia emission rates (ER, g/bird-d) of the commercial broiler houses among various U.S. studies

Reference	Growth Period, d	Stocking Density, (birds m^{-2})	Flocks	Litter	Mean ER, g/bird-d	Location
Burns et al. (2007b)	52	12.7	3	New	0.49	Kentucky, U.S.A
Burns et al. (2007b	52	12.2	9	Built-up	0.62	
Wheeler et al. (2006b)	42	14.7	10	New	0.47	Kentucky and Pennsylva nia U.S.A
	42	14.7	12	Built-up	0.65	
	49	13.4	24	Built-up	0.76	
	63	10.8	20	Built-up	0.98	
Burns et al. (2003)	42	16.1	9	Built-up	0.92	Tennessee , U.S.A
Lacey et al. (2003)	49	13.5	12	Built-up	0.63	Texas, U.S.A
Seifert et al. (2004)	42	20	1	Built-up	1.18	Delaware, U.S.A

Table 2. European ammonia emission rates for broiler housing (from Wheeler et al. 2006)

Reference	Market Age	Stocking Density (birds m^{-2})	Litter*	Mean ER g/bird-d
Müller (2003) German/Czech	32	n/a	New?	0.09
Demmers (1999) United Kingdom	32	25	New	0.11
Wathes (1997) United Kingdom	32	9.3 W 9.4 Su	New?	0.26
United Kingdom			New?	0.48
The Netherlands			New?	0.27
Denmark			New?	0.21
Germany			New?	0.44

Measurement systems and sampling protocols

Most housing emissions studies in the U.S. have recently settled upon a fairly standard set of equipment and protocols. This has arisen in part from Air Quality Consent Agreement between the USEPA and livestock and poultry groups. Researchers involved in these and related studies have developed a consistent set of techniques for most emitted constituents of interest (Burns et al., 2006, 2007c; Moody et al., 2006), and for the accurate determination of ventilation rates from buildings (Gates et al., 2004). However, the current approach relies on a reduced sample of sites (e.g. three broiler houses in the entire U.S.) and a high frequency emissions rate sampling strategy. This needs to be re-evaluated as baseline values are published.

While substantial recent progress is noted in determining baseline emissions for various US AFOs, there remain substantial unknowns. Since published baseline emissions are used as representative sources for design, for modeling and for regulation, the variability in baseline emissions, and more importantly the underlying factors which are responsible for this variability, need to be better understood and documented. Always, the measured variability should be reported.

For example, for the broiler emissions cited above, there is a strong linear correlation between daily emissions and bird age; the single average emission values per study in Tables 1 and 2 (expressed on a per bird per day basis) miss completely this key factor. Burns et al (2007a) noted that emissions factors reported for broilers can be misleading, depending on market age, bird age when emissions were measured, and whether new litter was used. They reported (mean ± std. dev.) emissions of 12.4 ± 9.4 kg/d-house (new litter flocks), compared to 14.6 ± 9.0 kg/d-house (built-up litter flocks).

A useful and cost-effective approach to sampling protocols utilizing less expensive monitoring equipment and more frequent, random visits to measure emissions has been developed in Europe (Mosquera-Lousada and Ogink, 2006; Vranken et al., 2004). This better captures variability within a farm over seasons and animal size, between farms on a similar day, and between farms over seasons. This sampling protocol is now the basis for performance evaluation of Dutch air mitigation systems. The use of less expensive monitoring equipment (Gates et al., 2005) and a larger sample of houses was the strategy employed in the US baseline ammonia emissions studies documented by Wheeler et al. (2006) and Liang et al., (2005, 2006). A comparison between this and the more sophisticated system appears quite favorable (Amaral et al., 2007).

The importance of documenting emissions variability

A need to quantify variability in emissions estimates has been noted by some researchers, e.g. Burns et al. (2007a), Mosquera-Lousada and Ogink (2006), Gates et al., (2008). Why is documenting the variability of housing emissions important? Frankly, without an understanding of the range in expected emissions profiles it is unlikely that reasonable mitigation technologies can be designed to fit an operation.

Consider a technology to scrub ammonia from building ventilation air. To design the scrubber system, one must determine typical, minimum and maximum design ventilation rates that will reasonably be expected to require treatment, and the typical air stream concentrations of ammonia at these design ventilation rates. If recently acquired emissions data are presented solely in terms of daily emissions rates per animal mass, then a designer will be forced to make some critical assumptions regarding air stream ammonia concentration, ventilation rate and their variability with bird age. This is despite the fact that this information has been collected as part of the emissions sampling!

Such an approach to design is a recipe for failure. The design failure could occur because the system was under-sized and did not perform to a minimum performance standard (which does not currently exist in the U.S.); or it could as readily be expected to fail because while it performs flawlessly, its construction cost and operating costs cannot be supported under the income stream generated by the AFO.

Proper engineering design of abatement technologies starts with a reduction in the number of critical assumptions made owing to a lack of pertinent data in the scientific literature.

MODEL DEVELOPMENT AND VALIDATION

Models have a key role to play in both developing mitigation technologies (e.g. unit operations and transport phenomena) and in assessing fate and downwind transport on local, regional, national and global scales. Model efforts for improving abatement technology designs are also a critical and evolving area.

Modeling research includes: local air dispersion modeling, local and regional impacts, permitting, emissions inventory models, and process-based modeling to enhance understanding of underlying phenomena and potential for mitigation. Properly developed and validated models are critical. Use of emissions measurement literature to develop, calibrate and validate such models requires appropriate documentation of the monitoring protocols, animal housing system, animal management issues including feed regimes, stocking density and weight, season, etc.

The range in measured variables, or some other means of expressing measurement uncertainty, is also critical for model input/output sensitivity. A simple example of the utilization of documented measurement uncertainty, coupled with features unique to broiler rearing, is in Gates et al. (2008), in which baseline emission results from Wheeler et al. (2006) were utilized to construct an ammonia emissions inventory that could be compared to USEPA estimates. Because Wheeler et al. (2006) provided estimates of uncertainty in their published baseline emissions, the inventory model was developed to predict emission inventory estimates and a measure of uncertainty in these estimates stated with an appropriate measure of statistical confidence.

Modeling for mitigation design strategies

Models are a key part of engineering design. A rich engineering literature exists for air treatment technologies; many developed and applied for decades in the chemical engineering journals. Air emissions mitigation can be accomplished by strictly chemical means (e.g. an acid scrubber for removal of ammonia), or by biochemical means (e.g. use of nitrifying bacteria to consume ammonia in a gas-phase biofilter). This latter technique has substantial prior research in wastewater treatment systems. Hence, model development for bio-based mitigation design strategies will emerge to provide a better understanding of design trade-offs. An example of a relevant, current model for gas-phase biofiltration for ammonia removal is presented by Baquerizo et al (2007). Further refinement, and development with an objective of model use for engineering design, remains as a significant barrier.

Modeling for fate and transport

Perhaps the most useful short-term application of models for fate and transport is for local dispersion of odors. Because odor complaints are a leading public nuisance issue (whether regulated *per se* or not), the fate of odors downwind of an AFO is of considerable importance and has been the focus of substantial US research and development for more than a decade.

Odor source variability includes some of the same issues as for gaseous emission variability, and odor dispersion models have substantial uncertainty. For example, a recent study by Henry et al. (2007) showed an excellent average relationship between predicted and measured odor concentrations but substantial range, with 64% of measurements falling within the range of predicted values. Despite such large uncertainty, odor dispersion modeling will be a critical facet for facilities siting, mitigation assessment, and related local regulatory issues.

A good example of odor model use for local transport is presented by Jacobson et al. (2005) and Guo et al. (2005), in which a science-based dispersion model for setback distances from AFOs was developed and assessed, using "annoyance curves". Substantial variability was observed for measured odor intensities and model predictions need further improvement; however this sort of approach is likely to be a critical component for assessing the performance of emissions mitigation technologies.

Regional and larger scale modeling is of particular interest for understanding the dynamics of fate and transport. It is also beyond the scope of farm-level air emission mitigation assessment, although of course there is a direct linkage between on-farm emissions and their contribution to larger-scale environment impacts.

MITIGATION EFFORTS

European research over the past two decades has advanced significantly, especially with regard to baseline quantification, measurement systems and protocols, and mitigation technologies for ventilation air. In part this is because of a different regulatory structure, with an emphasis on ammonia emission reduction and stringent permitting procedures for new facilities and renovations. The next speaker will elaborate on European progress.

Results from recent US baseline emissions quantification from AFOs have tended to be similar to that reported in the European literature; however this was not expected given the substantial differences in housing, feeding management and ventilation systems employed.

Numerous air emissions mitigation efforts have been studied in recent years in the U.S. These efforts include: dietary manipulation, feedlot and building dust control, management of housing, manure and ventilation, ventilation air dispersion techniques, manure and litter amendments, and treatment systems for housing and waste storage ventilation airstreams.

Opportunities for Mitigation

Efforts to mitigate emissions from AFOs can be divided into pre- and post-generation. In principle, methods to reduce the potential for emissions are attractive since they can also improve the economics and consequently create an added incentive for rapid adoption by industry.

<u>Feed supplements and Dietary Manipulation</u>
Dietary manipulation is a key example of a pre-generation mitigation opportunity. Animals are fed nitrogen in the form of crude protein, and if key amino acids are supplemented to better match biological function at different phases of growth, the crude protein is used more efficiently. Often, the resultant diet is more cost-effective than typical' diets, and this cost-savings will continue to accelerate as use of crystalline essential amino acids becomes more prevalent and less expensive. Better matching feed ration to animal requirements results in less nitrogen loss to the feces, reduced potential for ammonia formation (Ferguson et al. 1998a,b), and has been shown to be a viable means of ammonia reduction on a commercial scale (Liang et al., 2005, 2008).

Additionally, substantial research on various feed supplements targeted toward improved feed conversion efficiency has been performed over the past two decades. Strategies to enhance gut flora with "enzyme cocktails", improve phosphorus uptake efficiency by feeding phytase, and use of various plant extracts to alter feces composition and subsequent breakdown are widely reported in the literature. Certain of these strategies have been widely adopted, for example the mandatory use of phytase in broiler diets on the Delmarva Peninsula, while others appear to have more limited adoption.

Facilities Design:
Another opportunity for air emissions mitigation includes facilities design. This is not strictly a "pre-generation" opportunity, but if key elements are included in the design of facilities, they effectively stop or reduce emissions prior to production. Key examples include:

Separate feces from animals and their housing: manure belts in egg layer housing are one example of a technology that is rapidly gaining favor. Belts allow rapid drying of feces which in turn suspends microbial activity, and removal of feces to a storage area that does not need ventilation at the rate that a production house requires for laying hen comfort.
Remove urine from feces and transport either or both out of the livestock area. Opportunities include new floor designs that actively shunt urine away from feces.

Solid-liquid separation to take advantage of existing waste-water treatment technologies. This technology is mature, and collection of manure for example in shallow that are flushed regularly, rather than in deeper pits that serve as storage, can reduce housing emissions.

Energy-efficient building ventilations system designs: there is no substitution for proper quantities of fresh air, delivered to the animals, in modern facilities. The fundamental trade-off however between the need to temper fresh air for some species (e.g. poultry and swine) and the energy cost of this tempering, is a leading cause of ventilation reductions which in turn spawn a host of problems including poor indoor air quality. Technologies to improve energy efficiency, such as use of attic tempering for ventilation air in broiler chickens, biomass gasification to provide supplemental heat, and use of compact fluorescent lighting to reduce electrical load are examples that are not generally recognized as directly relating to air emissions mitigation. Outreach and education, as well further research and development, are clearly needed to change perceptions on the importance of ventilations system design and operation to control air emissions.

Physical barriers to odor and gas transport, such as waste storage pond covers, and active capture and treatment of methane digester headspace emissions.

Note that these mitigation strategies must be part of a whole system approach, i.e. mitigating housing emissions by means of moving manure out of the facility means that the manure storage facility design is also important. Further, regardless of design feasibility, proper management is critical. There is tremendous opportunity to improve both design and facilities management by a closer coupling between design engineers and producers. Opportunities for technical service providers to provide this coupling are currently limited owing to the lack of economic incentives for either party.

Post-generation technologies

Post-generation technologies include a broad array of activities, including feedlot and building dust control, management of housing, manure and ventilation, ventilation air dispersion techniques, manure and litter amendments, and treatment systems for housing and waste storage ventilation airstreams. Some of these are briefly reviewed below.

Room air treatment
Room air treatment technologies that have been tried but have not been successful include dust control with oil spraying (effective, but messy), ozonation (Elenbaas-Thomas et al., 2005) and odorant masking.

Ventilation air treatment
Ventilation air treatment technologies include ozonation and odorant masking, neither of which has proven to very effective. Other more promising technologies include means for dust and gaseous emissions reduction. One simple technique that is becoming better understood is use of windbreak walls downstream of exhaust ventilation fans. The walls can be a combination of physical barriers to divert exhaust air (Figure 1), vegetative buffers to physically capture dust from the exhaust air, or vertical chimneys for improved dispersion. These techniques rely primarily on physical treatment to remove dust, which in turn reduces odor and certain gas emissions; or improved physical dispersion which acts to improve downwind odor concentrations but does not treat the ventilation air.

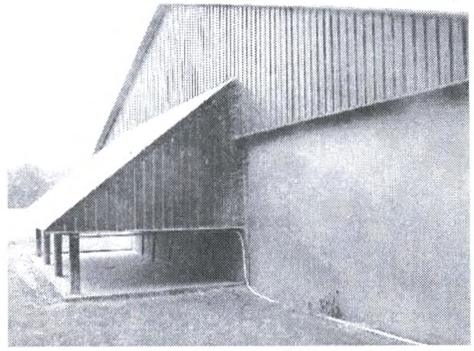

Figure 1: A simple physical barrier around exhaust ventilation fans to reduce dust emissions.

Active treatment of AFO ventilation air for odor or gaseous emission controls are emerging in the US. These include scrubbers, for example, acid scrubber for ammonia removal (Manuzon et al., 2007); and gas-phase or trickling biofilters for ammonia and/or odor mitigation (Baquerizo et al. 2007; Maia et al., 2006; Nicolai at al., 2006; Devinny et al., 1999; Zhang, 2005). Design criteria, and practical engineering details including ways to bring ventilation air to a piece of treatment equipment, are generally lacking and seen as substantial hurdles to current adoption. Their inclusion in new facilities is more likely in the shorter term.

Aerobic biofilters are gas-phase heterogeneous reactors which convert contaminants into CO_2, water vapor and organic biomass (Devinny et al., 1999). Biofiltration uses different processes to remove pollutants in the air stream including biodegradation, adsorption, desorption and absorption. The liquid phase in a biofilter is stationary where microorganisms organize themselves as a biofilm on the surface of the medium or are suspended into the water phase close to the medium to convert organic matter into more stable and biodegradable forms.

A concern with gas-phase biofilters is that incomplete denitrification may result in elevated production of N_2O, a problem not as likely to be encountered in trickling film biofilters such as in waste-water treatment facilities. Since N_2O is a strong greenhouse gas, its generation during the breakdown of ammonia would be an unwelcome side effect. An example gas-phase biofilter system being tested for waste storage headspace gas treatment is illustrated in Figures 2 and 3 (Maia et al., 2006). Regardless, gas-phase biofilters show great promise to handle particulate matter loading and to mitigate both odors and gaseous emissions.

Several challenges exist when devising new strategies to handle ventilation air.

- First, the sheer volume of air that is utilized to maintain temperature and humidity within facilities can be a significant obstacle for engineers trained in “stack” industry abatement technologies. It is suggested that substantial treatment of some ventilation air, especially for odor abatement, may be more practical than complete treatment of all air.
- Second, ventilation air is generally contaminated with substantial particulate matter that can rapidly degrade scrubber or biofilter performance if not treated (see Figure 4).
- Third, these volumes of ventilation air are provided by propeller fans that often have marginal performance curves and so the addition of any significant downstream treatment which includes additional pressure drop will require fan replacement, consume greater energy per unit volume of air moved, and require facilities re-design (or remodeling) to capture and treat this airflow (see examples in Figure 5).
- Fourth, many facilities (e.g. dairy free-stall barns, turkey growout barns) rely on natural ventilation, making treatment impossible.

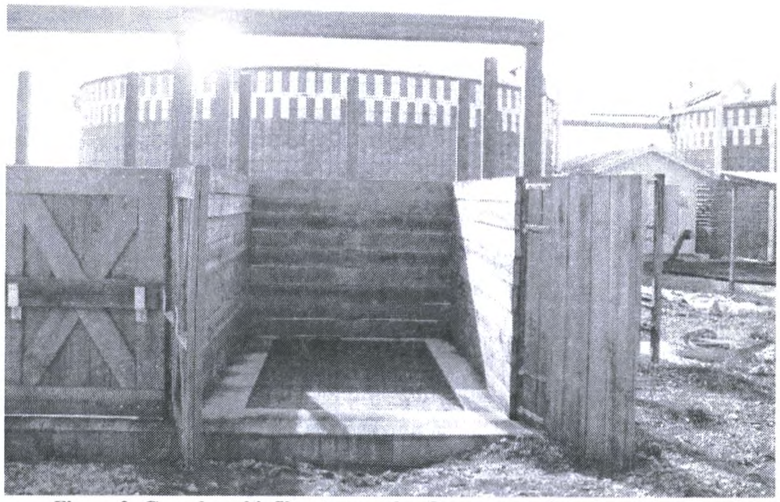

Figure 2: Gas-phase biofilter to treat headspace gases for odor and ammonia.

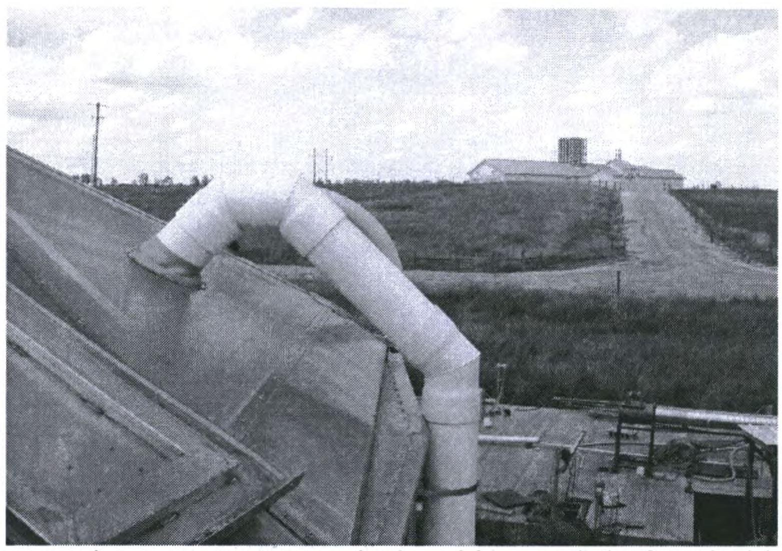

Figure 3: Treatment of headspace gases in waste storage structures involves minimum ventilation for maintaining methane concentration below explosive limits and hydrogen sulfide below dangerous limits, and downstream treatment of the exhaust with gas-phase biofiltration for odor and ammonia removal (see Figure 2). Background: the swine facility utilizes exhaust stacks for high velocity ejection of ventilation air, pull-plug gravity flow systems for manure handling, collection into an in-ground tank (concrete pad in middle-ground), and storage in two above-ground impermeable tanks for twice-annual pumping to direct injection sites for crop fertilizer.

Manure and Litter Amendments

This encompasses a variety of techniques including physical drying and separate storage of feces, acid-based amendments to control pH of litter, bedding or manure pack and thereby reduce ammonia volatilization, and application of urease inhibitors to stop the breakdown of uric acid. Each has clear potential under certain applications. Each presents management challenges. Most need additional investigation of economic trade-offs.

Examples include:

- Use of broiler litter amendments to reduce ammonia volatilization in housing are often coupled with reduced minimum ventilation settings that provide poor control of litter moisture. As the effect of the amendment wears off (after about 3 weeks or less) the litter is wet and ammonia concentrations in these houses can rise above those that were ventilated to recommended rates and did not use litter amendment (Casey et al., 2005).
- Urease inhibitors can be used to stop the enzymatic activity that breaks down uric acid and creates ammonia (Singh et al., 2005). Commercially available inhibitors in the US tend to be most effective on materials at higher moisture content, although work on beef cattle feedlots (Parker et al., 2004; Shi et al., 2001) and broiler litter (Singh et al., 2005) have shown limited success. Recent German studies have involved proprietary inhibitors that appear to work at lower media moisture contents (Hartung, E. personal communications, June 2006).

- Alum and other acid-based amendments to layer feces in high rise layer housing. Problems with liquid alum application are primarily related to its caustic action on building materials.

Other Opportunities

A likely increase in on-farm biogas production is expected as energy costs continue to increase and more uniform acceptance of on-site electricity generation occurs. With increased incidence of captured slurry under cover, there will be a reduction in fugitive odor emissions and in baseline gaseous emissions from a facility. By moving the waste from a building, ventilation requirements during cold weather (for indoor air quality) are greatly diminished. Treating a relatively low volume of methane digester headspace gas may be more economically viable.

An economic incentive for adoption of air emission mitigation technologies may be realized as carbon credit trading is further developed in the US. Regular payments for utilizing a mitigation technique could be a key factor for adoption.

A need for increased energy efficiency in confinement AFOs will likely cause a renewed focus on improved facilities and ventilation system engineering. As existing facilities age, their replacement with newer designs will afford an opportunity for abatement technologies to be designed "from the ground up".

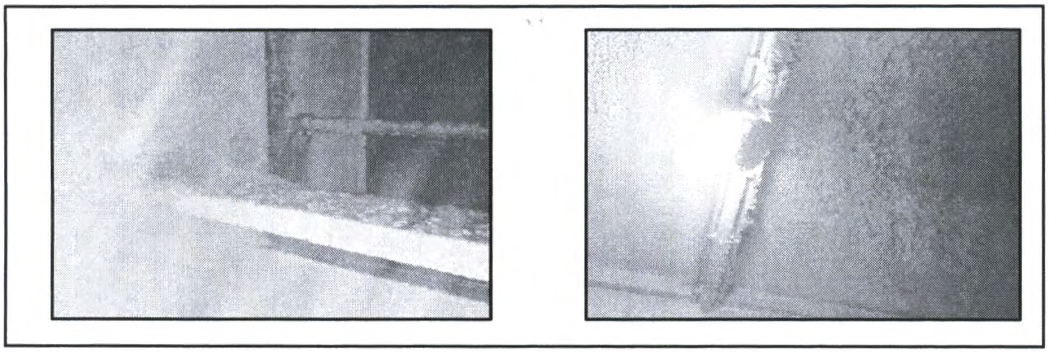

Figure 4: Dust in ventilation exhaust air remains a substantial challenge to mitigation technologies. Seen in these photos is dust accumulation in a broiler house upstream of a scrubber/biofilter assembly. Substantial dust clogging impairs scrubber operation and creates a maintenance headache.

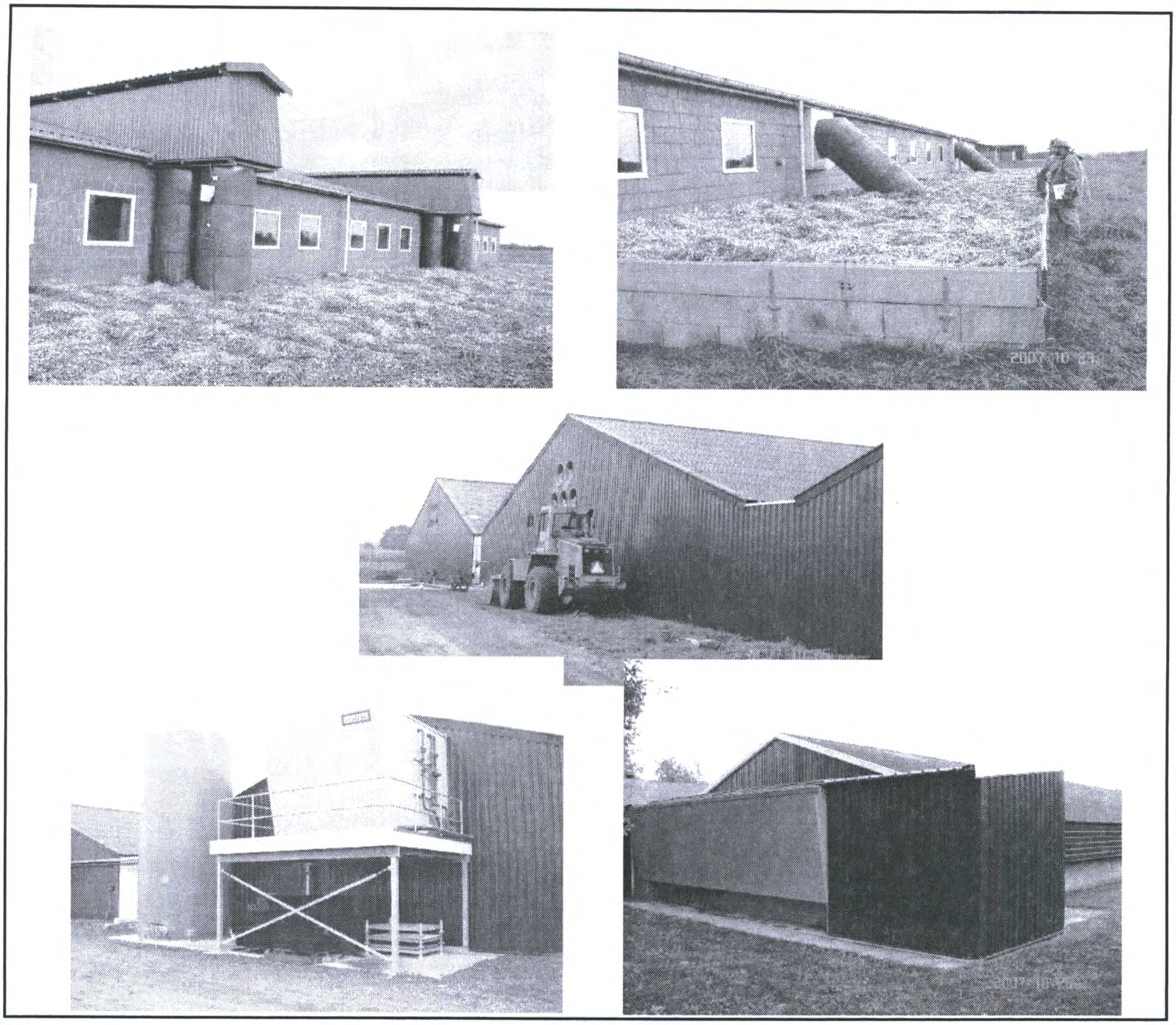

Figure 5: Treating ventilation air from AFO structures involves substantial facilities engineering and increased energy costs for even the simplest of AFOs. Top: two open air, horizontal biofilters for treating swine barn ventilation air. Center: a swine barn ventilation system being prepared for downstream mitigation. Bottom: a swine barn (left) and broiler barn (right) with ventilation air treatment systems. Summary

SUMMARY

The state of the science for US Animal Feeding Operations emissions mitigations is maturing. Specific mitigation techniques are needed to control gaseous and odor emissions in an efficient and cost-effective manner. There is currently no consistent federal policy nor regulation regarding air emission mitigation strategies, although there is substantial development of best management practices and best available technologies that have been, and continue to be developed. The current regulatory environment does little to encourage new mitigation approaches as part of best management practices; litigation often drives adoption of a best available technology among a limited selection of choices with unclear economic and technical feasibility.

It is likely that a host of mitigation techniques will be needed to address continued air emissions concerns. Rather than looking for a single "silver bullet" solution a more reasonable approach is to select cost-effective combinations that match the economic, management and, perhaps regulatory constraints that vary regionally and by species. To accomplish this, a substantial effort is needed. While great progress has been made in some areas of AFO air emissions, substantial commercial-scale evaluation and validation is necessary.

The following comments are offered:

- Substantial work remains to develop and implement mitigation systems that are effective and cost-efficient.
- There is a lack of a cohesive national plan to develop abatement policies tied to performance criteria.

- Substantial recent progress has been made on US AFO emissions baseline estimates, but researchers and peer-reviewers must ensure that the inherent variability in these measurements is quantified and reported. Without this key understanding, process-based models that explore interactions among contributing factors cannot be properly validated, but they will be used as needed in the growing regulatory focus on AFO operation and especially in new facility permitting.

- There is tremendous opportunity to improve both mitigation design and facilities management by a closer coupling between design engineers and producers.

- Outreach and education, as well further research and development, are clearly needed to change perceptions on the importance of ventilations system design and operation to control air emissions.

- A useful and cost-effective approach to sampling protocols utilizing less expensive monitoring equipment and more frequent, random visits to measure emissions has been developed in Europe.

- Active treatment of AFO ventilation air for odor or gaseous emission controls are emerging in the US.

- The sheer volume of air that is utilized to maintain temperature and humidity within facilities can be a significant obstacle for engineers trained in "stack" industry abatement technologies. It is suggested that substantial treatment of some ventilation air, especially for odor abatement, may be more practical than complete treatment of all air.

- A concern with gas-phase biofilters is that incomplete denitrification may result in elevated production of N2O, a problem not as likely to be encountered in trickling film biofilters such as in waste-water treatment facilities.

- With increased incidence of captured slurry under cover, there will be a reduction in fugitive odor emissions and in baseline gaseous emissions from a facility.

- Regular carbon credit payments for utilizing a mitigation technique could be a key factor for adoption.

- As existing facilities age, their replacement with newer designs will afford an opportunity for abatement technologies to be designed "from the ground up"

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Exhaust Air treatment systems in Europe

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Keywords. *exhaust air treatment system, waste air treatment, biofilter, biological scrubber, trickle bed reactor, chemical scrubber, multistage air treatment systems*

Introduction

To comply with European emission threshold levels associated with animal husbandry, the emissions of ammonia, dust and/or odor has to be reduced significantly. Especially in regions with high animal densities the initial level of pollution already meets the set emission threshold levels in many cases. In these cases exhaust air treatment becomes a very appropriate measure to achieve a distinct emission reduction.

In Europe air purification systems are applied in general only at animal facilities designed with forced ventilation with locally defined air outlets, point sources respectively. For animal facilities with natural ventilation such as cattle and more and more poultry and pig stalls, where the air outlets are rather no point sources, normally no air treatment systems are employed.

Exhaust air treatment techniques applied at animal facilities for the "intensive rearing of poultry and pigs" are currently not ranked as BAT (Best Available Techniques) and hence are no part of the European reference document (BREF). At the same time, process technology has made good progress. In addition to classic biofilters and biological scrubbers (trickle bed reactors), chemical scrubbers and multistage treatment systems have established themselves especially in Germany.

Moreover, to support well designed and practicable air treatment systems in Germany, which achieve a defined minimum/average reduction performance, a testing procedure and certification called "SignumTest" was introduced in co-operation by a scientific expert group, the Association for Technology and Structures in Agriculture (KTBL) and the German Agricultural Society (DLG) Germany in 2006/2007. The SignumTest is by nature a utility value test. As the name implies, the test assesses the value of a product in practical testing, which is based on a test procedure devised by an impartial expert commission. The commission assesses the test results in accordance with fixed assessment standards and awards the DLG SignumTest symbol.

Overveiw of and requirements for air treatment techniques

At the present biofilters and biological scrubbers (trickle bed reactors), chemical scrubbers and multistage treatment systems are predominantly applied to treat the waste air from animal facilities with regard to the separation of total dust, ammonia, and/or odor. Table 1 gives an overview of air treatment systems currently used and on the main requirements to be met to achieve the German SignumTest award.

The use of single-stage biofilters for ammonia removal in animal housing is not recommended. Large quantities of enriched nitrogen lead to the formation of secondary trace gases and fast material decomposition so that the operation period of the filter material is shortened significantly. For odor reduction, however, they are very suitable.

For trickle bed reactors without pH-control, the required ammonia separation rate of 70 % is only reached at elutriation rates of ca. 0.2–0.3 m^3 per kilogram of ammonia input. At the mentioned elutriation rate, scrubbing water regeneration is not required.

Chemical scrubbers provide little odor reduction because the low pH-value prevents the colonization of the filter walls by microorganisms. For this reason, they are not suitable for odor removal. In the clean air, the odor of waste air is regularly perceptible. Due to their very high ammonia separation capacity, chemical scrubbers are generally operated as two or three-stage installations and combined with trickle bed reactors or biofilters.

A two-stage installation consisting of a wet and a chemical scrubber also provides good odor reduction in pig housing. For poultry husbandry, currently no results are available. Two-stage installations are very suitable for dust reduction. Given the large total dust loads in littered housing, however, frequent treatment of the first process stage is indispensable. The treatment intervals should be determined and documented based on differential pressure measurements. The sprinkling density of the first stage should be considerably above the sprinkling density of the second stage. Like in trickle bed reactors, ammonia absorption capacity in the water stage of two stage installations is limited. In these systems, the combination of a water stage and a biofilter leads to ammonia being entrained into the biofilter. Only high elutriation rates (0.2–0.3 m^3 per kilogram of ammonia input) allow good results to be achieved. However, this combination is very suitable for odor reduction and dust separation.

Table 1. Suitability of exhaust air treatment systems for forced ventilated animal housing facilities.

Treatment System	Utilization	Housing System	Assessment of Reduction Efficiency		
			Total Dust	Ammonia	Odor
Biofilter	pigs, cattle	not littered systems	+	n. g.	++
Biological Scrubber	pigs, cattle	not littered systems	+	+	+
Chemical Scrubber	pigs, cattle, dry poultry dung store	not littered systems	+	++	n. g
Multistage air treatment systems *two-stage*	pigs, cattle, poultry	littered and not littered systems			
• Wet Scrubber & Chemical Scrubber			++	++	0 / +
• Wet Scrubber & Biofilter			++	0 / +	++
• Chemical Scrubber & Biofilter			++	++	++
• Chemical Scrubber & Biological Scrubber			++	++	+
three-stage	pigs, cattle, poultry	littered and not littered systems			
• Wet Scrubber & Wet Scrubber & Biofilter			+++	+	++
• Wet Scrubber & Chemical Scrubber & Biofilter			+++	+++	+++

n. g.: unsuitable; 0: conditionally suitable; +: suitable; ++: good; +++: very good

Three-stage installations with two water stages and a biofilter stage are also only suitable for ammonia separation if they have such a high elutriation rate. As compared with two-stage systems in the same combination, however, they allow dust to be separated even better.

Removal efficiency

With regard to odor reduction, certified trickle bed reactors and multiple-stage systems meet the criteria of the DLG SignumTest test frame (no waste air odor is perceptible in the clean air). For trickle bed reactors, this requires the observance of the described elutriation rates. Single-stage chemical scrubbers are not suitable for odor reduction because they do not fulfill the criteria of the test frame. Given appropriate design and operation, biofilters can also meet the criteria of the test frame. This requires that the filter material is kept sufficiently moist at any time. With the exception of the biofilter, all systems can be used for the reduction of ammonia emissions if they are designed properly even though their efficiency is different. Trickle bed reactors must also reach sufficient elutriation rates. All systems can meet the dust separation requirements for certification. In order to avoid the discharge of scrubbing water droplets into the environment, scrubbers must be equipped with a functioning drip separator at the outlet.

Process control, documentation, and monitoring

DLG certified systems allow the decisive functional parameters, such as the pH-value, sprinkling density, and the elutriation rate, to be controlled efficiently. In agricultural biofilter systems, malfunctions are difficult to detect. This in particular applies to the drying of the filter material from the waste air side. In addition, there are few possibilities of intervention. Effective process control and monitoring require an electronic operations logbook where the decisive operational parameters, such as pressure loss in the exhaust air treatment system, the air flow rate, media consumption, and the pH-value, are recorded. In the case of a conflict, this enables the proper operation of the system to be documented.

Costs

Virtually regardless of the technique and considering the cost degression provided by larger systems in pig fattening, total annual expenses in the amount of € 13 to 17 per animal place or € 5 to 6 per animal (without VAT) can be assumed as planning values for the construction and the operation of certified exhaust air treatment systems in combination with the new construction of an animal house. Based on a system capacity of 1,000 m^3/h, total expenses in the amount of € 140 to 200 per year can be expected. In the relevant capacity range of 50,000 to 150,000 m^3/h, cost degression is approximately 20 to 30 %. The costs include the most important factors which can be considered part of exhaust air treatment. They not only comprise the investment and operational expenses of the exhaust air treatment systems themselves, but also the additional requirements for housing ventilation as well as wastewater storage and spreading.

Recommendations

When planning an animal housing construction project with an exhaust air treatment unit, the owner must first consult advisers, experts, and the competent authority in order to find out which emissions of the animal housing facility cause problems in the neighborhood (odor, ammonia, and/or dust) and to what extent these emissions should be reduced.

In any case, it must be examined whether all possibilities of reducing the emissions by means of process-integrated measures in the animal house have been exhausted. These measures include optimized feeding and temperature control in the animal house, for example, or reductions at other sources, such as existing animal houses and slurry storage. In addition, it is necessary to determine whether the emission impact situation can be improved by means of better exhaust air conduction, e. g. in the form of a central exhaust air system. In a location analysis, a relocation of the construction project including a (partial) relocation of the farm to the outer area can also be examined as an alternative.

The choice of the treatment technique mainly depends on which emissions are intended to be reduced and which removal efficiency is necessary. In principle, only systems should be used which have been certified.

Measures for the reduction of the summer air flow rate, such as cooling, allow the dimensions of the exhaust air treatment system to be reduced and might lower the investment requirements and operational expenses significantly. Moreover, the operational expenses can be lowered if emissions are kept to a minimum by keeping animal houses dry and clean. If the air in the animal house is less polluted, fewer operating resources are consumed, and the service periods of the filters until the next treatment increases, which reduces the maintenance requirements. In addition, the flow resistance of the system and the electricity consumption are lower.

Several suppliers of certified exhaust air treatment systems should be asked to submit offers. The offers should contain the most important specifications for the proper design of the system. The offers should show the costs of the system and the expenses for the building shell as well as the specific expenses for the treatment of 1,000 m^3/h of exhaust air or per kilogram of ammonia separately so that the offers can be compared with regard to the prices.

In any case, reference systems should be visited and information from colleagues who operate similar systems should be obtained. Easily understandable, extensive system descriptions are also a sign of quality.

During planning and construction, the ventilation system of the animal house should be adapted to operation with an exhaust air treatment system. It should also be designed optimally with regard to air flow pattern, so that the filter surfaces are exposed to an even flow and the pressure loss, flow resistance respectively of the entire system is as low as possible. It is particularly important that sufficiently pressure-stable fans are used which can compensate the additional flow resistance of the exhaust air treatment systems of up to 150 Pa depending on the kind of system and the operating state. It must be guaranteed that the ventilation system can provide the required air flow rates with regard to animal welfare at any time.

In principle, the serviceability and the removal efficiency of the unit should be guaranteed in writing by the manufacturer. This also applies to the documentation which proves that the water protection regulations of the federal states and the work and chemical safety regulations are observed. After its construction, the system should be approved according to the requirements of the certification test. In general, a maintenance contract with the manufacturer is recommended. In addition, the owner should assume the responsibility for checking the system regularly (i.e. daily), and the system should be maintained no later than after the service intervals recommended by the manufacturer or in the test certificate. The operation of the system should also be monitored by the competent licensing authority.

The ammonium quantity contained in the wastewater should be considered in fertilizing management. The percentage of ammonium can easily be measured on the premises with the aid of quick tests. In scrubbers with an acid stage where sulfuric acid is used, the elutriated wastewater contaminated with ammonium sulfate must be stored in a separate container.

Acknowledgements

Special thanks to all authors of the KTBL-Schrift 464 "Exhaust Air Treatment Systems for Animal Housing Facilities; Techniques - Performance - Costs": F. Arends, Chamber of Agriculture Lower Saxony, Oldenburg; G. Franke, Hessian State Institute of Agriculture, Kassel; E. Grimm, Association for Technology and Structures in Agriculture (KTBL), Darmstadt; W. Gramatte and S. Häuser, German Agricultural Society (DLG), Test Centre for Technology and Farm Inputs, Groß-Umstadt; Dr. J. Hahne, Federal Research Institute for Rural Areas, Forestry and Fisheries (vTI), Braunschweig;
Special thanks to all members of the cooperating KTBL working group "Status of Process Engineering and Costs of Exhaust Air Treatment in Farm Animal Housing": F. Arends, Chamber of Agriculture Lower Saxony, Oldenburg; Dr. G. Brehme, Consultant, Coswig (Anhalt); Prof. Dr. W. Büscher, Rheinische Friedrich-Wilhelms-Universität, Bonn; Dr. J. Clemens, Rheinische Friedrich-Wilhelms-Universität, Bonn; F. Eichler, Federal Environment Agency (UBA), Dessau; G. Franke (chairman), Hessian State Institute of Agriculture Kassel; E. Grimm (managing director), Association for Technology and Structures in Agriculture (KTBL), Darmstadt; Dr. J. Hahne ,Federal Research Institute for Rural Areas, Forestry and Fisheries (vTI), Braunschweig, Prof. Dr. E. Hartung, Christian-Albrechts-Universität, Kiel Dr. M. Mußlick, Thuringian Ministry of Agriculture, Nature Protection and the

Environment, Erfurt; Dr. J.s Seedorf, Foundation of the School of Veterinary Medicine Hanover, Hannover; Prof. Dr. H. Van den Weghe, Research and Study Centre for Animal Production and Technology Weser-Ems of Göttingen University, Vechta.

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A REVIEW OF AMMONIA EMISSIONS MITIGATION TECHNIQUES FOR CONCENTRATED ANIMAL FEEDING OPERATIONS

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INTRODUCTION

Several approaches have been suggested and evaluated for reducing ammonia emissions from excreted animal manure; reduction of nitrogen excretion through dietary manipulation, reduction of volatile ammonia in the manure to stop ammonia loss, and segregation of urine from feces to reduce or stop contact of urease and urine. When urine-feces segregation is not an option, urease inhibitors can be used to reduce or eliminate the hydrolysis of urea into ammonia. Methods for reducing volatile ammonia in manure include the reduction of pH, which shifts the equilibrium balance in favor of ammonium over ammonia, use of other chemical additives that bind ammonium-N, and use of biological nitrification-denitrification to convert ammonium into other N-species such as nitrite, nitrate, or gaseous nitrogen. Other methods for mitigating ammonia emissions target emitting surfaces, and include capturing (using physical covers) and treating captured air to remove ammonia (using biofilters or biocovers, and scrubbers), and direct manure injection or incorporation into the soil. Manure collection facility designs and appropriate facility management are also essential for abating ammonia emissions. This article provides a review of these approaches in the context of concentrated animal feeding operations.

MITIGATION MECHANISM:

Ammonia emitted from concentrated animal feeding operations (CAFOs) may soon be subjected to state and federal regulations aimed at protecting air resources when data for estimating emissions to the atmosphere from CAFOs have been collected from an ongoing National Air Emission Monitoring Study (NAEMS). This NAEMS is funded by the Agricultural Air Research Council, a non-profit organization that receives its funds from livestock industry groups, and is being overseen by the EPA Office of Air Quality Planning and Standards. Thus there is a need to identify as well as develop practices and technologies to assist producers to prevent or mitigate ammonia emissions, not only for CAFOs to meet regulations requirements but also for livestock producers to be good environmental stewards.

Ammonia volatilization is one of the pathways for N loss from animal feeding operations. Ammonia volatilization is a critical issue because it represents a loss of fertilizer value and can adversely impact the environment (McGinn and Janzen, 1998). Ammonia can also be deposited from the atmosphere and may be beneficial to plants as a nutrient (N) source for growth. Conversely, when excess N is deposited in N-sensitive ecosystems, the N may impact these systems negatively. Potential consequences associated with exceeding threshold concentrations of both oxidized and reduced forms of N in the environment include: (1) respiratory diseases caused by exposure to high concentrations of fine particulate aerosols ($PM_{2.5}$); (2) nitrate contamination of drinking water; (3) eutrophication of surface water bodies resulting in harmful algal blooms and decreased water quality; (4) vegetation or ecosystem changes due to higher concentrations of N; (5) climatic changes associated with increases in nitrous oxide (N_2O); (6) N saturation of forest soils; and (7) soil acidification through nitrification and leaching (Kirchmann et al., 1998; Kurvits and Marta, 1998; Jongbloed et al., 1999).

The objective of this paper is to review the state of the science on the mitigation of ammonia from animal feeding operations with a view of summarizing the information on the effectiveness of current mitigation strategies on the reduction of ammonia emission. Strategies for reducing NH_3 losses from CAFOs (Table 1) are directed towards reducing: (1) NH_3 or NH_4^+ formation or production, (2) NH_3 losses after it has been formed, and (3) volatile N species. Some specific potential control strategies for NH_3 control from animal production facilities include changes in diet, barn design or retrofits, cleaning building exhaust air, manure treatment methods, and land application techniques. In practice, to obtain adequate NH_3 volatilization abatement in animal production operations a combination of these control strategies are used.

Table 1 - Summary of ammonia abatement strategies in concentrated animal feeding operations

	Source or Location			
	Excreted Manure and Urine	Confinement Facilities	Treatment & Storage	Land Application
Control Practice	• Reduce N excreted by reduced protein diets or improved balance of amino acids. • Dietary electrolyte balance, affecting urinary pH.	• Minimize emitting surface area. • Remove manure frequently (belt transport, scrape, or flush). • Filter exhaust air (bioscrubbers, biofilters, or chemical scrubbers). • Manure amendments (acidifying compounds, organic materials, enzymes, and biological additives).	• Cover to reduce emissions or collect gas. • NH_3 stripping, absorption and recovery. • Chemical precipitation e.g. struvite. • Biological nitrification (aerobic treatment). • Acidifying manure.	• Injection or incorporation into soil soon after application. • Application method to reduce exposure to air (e.g. low-pressure irrigation near surface, drag or trail hoses). • Acidifying manure.

1. Reduction of Nitrogen Excretion

Minimizing nitrogen excretion, which can be achieved through dietary-modifications, is naturally the first line of defense in curbing ammonia emissions from livestock operations (Satter et al., 2002). Available research data indicates that diets fed to animals have profound effects on ammonia emissions from excreted manure. Overfeeding dietary protein, imbalanced amino acid supply, and reduced energy availability for ruminal fermentation in ruminants result in increased urinary and fecal N losses and consequently increased ammonia emissions from manure.

In non-ruminants (for example; pigs), N excretion has been reduced by either shifting N excretion from urine to feces by increasing fiber in the feed or reducing the N content in the diet (Canh et al., 1997; Canh et al., 1998b). Reports indicate that feeding low CP diets to pigs can reduce (28-79 %) N excretion in the manure (Hobbs et al; 1996; Canh et al., 1998a). Panetta et al. (2006) reported decreased ammonia emission rates from 2.46 to 1.05 mg/min with decreasing dietary CP levels from 17.0 to 14.5%. Similarly, O'Connell et al. (2006) observed increased ammonia emissions from pig slurry from a 22 against a 16% CP in the diets. For broiler and layer chickens, reduced protein diets have resulted in reduced N excretion (Jacob et al., 2000). Thus, with some few notable exceptions (McGinn et al., 2002; Clark et al., 2005), reduction of dietary CP result in significant reduction in ammonia loss from pigs (Otto et al., 2003; Hayes et al., 2004; Velthof et al., 2005) and poultry (Ferguson et al., 1998; Nahm, 2003) operations. Other strategies such as supplementation of the diet with zeolite (Meisinger et al., 2002; Kim et al., 2005), antibiotics and probiotics (Han and Shin, 2005), vegetable oil (Leek et al., 2004), plant extracts (rich in tannins and saponins; Colina et al., 2001; Vliwisli et al., 2002), and exogenous enzymes (Smith et al., 2004; Clark et al., 2006; O'Connell et al., 2006) have been used with varied success to reduce ammonia losses from pig and cattle manure. In practice efforts to reduce ammonia emissions must be balanced with effects on animal performance in determining optimal protein concentrations and forms in the diet (Cole et al., 2005; Panetta et al., 2006).

In ruminants (cattle; for example), diet composition as well can have significant effects on urinary urea excretion and consequently ammonia losses from manure and overall efficiency of utilization of dietary N (Klopfenstein et al., 2002; Satter et al., 2002). Generally, ruminants are relatively inefficient utilizers of dietary N. The efficiency of transfer of feed N into milk protein N (MNE) is on average 24.7±0.14%, with a min and max of 13.7 and 39.8%, respectively (Hristov et al., 2004a); the remaining N being lost to the environment from urine and feces. In dairy cows, urinary N losses linearly decrease with decreasing dietary CP levels without affecting milk and milk protein yields and composition; MNE of 36% was achieved with the lowest CP diet (13.5%; Olmos Colmenero and Broderick, 2006). Cows fed 15.0 to 18.5% CP diets produced similar milk yields (32 to 39 kg/d) while simultaneously increasing N excretion and urinary N proportion (Groff and Wu, 2005). Reduction of N excretion from dairy cows can be achieved mainly by the reduction of N intake in the form of ruminally degradable protein (RDP; Kebreab et al., 2002). Utilizing a combination of prediction equations (urine volume) and actual analyses (urine composition), de Boer et al. (2002)

demonstrated the importance of the ruminal N balance (OEB) in reducing N losses in dairy cows. Increasing OEB from 0 (maximal utilization of RDP) to 1,000 g cow^{-1} d^{-1} resulted in linear increase in urinary N excretions. Feeding excess RDP resulted in greater ruminal ammonia and milk urea N concentrations and increased urinary N losses (by 27%; Hristov et al., 2004). Decreasing CP in diets fed to cows in mid [17 to 15% CP, ruminally undegradable protein (RUP) of 5.5 to 7.3], or late lactation (14 to 12.5% CP) can reduce the cost of the diet and waste N excreted from the cow. However, early lactating dairy cows need sufficient dietary RUP. After peak milk and DMI, CP and especially RUP requirements decline with declining milk production (Kalscheur et al., 1999).Using ruminally-protected amino acids enables an efficient use of low CP diets for production purposes. With ruminally-protected methionine (up to 25 g/d), milk yield was maintained and MNE increased from 26 to 34% as dietary CP decreased from 18.6 to 14.8% (Broderick, 2005). Methionine supply to low (13%) CP diets decreased proportion of urinary N in the total excreta N (Krober et al., 2000). Carbohydrate level and availability in the diet can also have a significant effect on ruminal ammonia utilization and consequently urinary urea output. Increasing dietary net energy of lactation concentration from 1.55 to 1.62 Mcal/kg decreased urinary urea N excretion and increased MNE (from 25 to 30%, respectively), while increasing dietary CP level from 15.1 to 18.4% had an opposite effect by increasing urinary urea N excretion and decreasing MNE (Broderick, 2003).

Dietary CP levels and effects on urinary urea excretion are directly related to ammonia emissions from cattle manure. Smits et al. (1995) fed dairy cows two diets differing in ruminally available protein (OEB; 40 vs. 1,060 g/d) and reported a significant increase in urinary urea-N concentrations and ammonia emissions from manure (by 39%) with the high-OEB diet. Külling et al. (2001) demonstrated that at 17.5% CP in the diet, N losses from manure after 7 weeks of storage were from 21 (slurry) to 108% (urine-rich slurry) greater than the N losses from manure from cows fed 12.5% CP, with respective ammonia emissions rates of 163 and 42 µg m^{-2} s^{-1}. Low protein diets (13.5-14% CP) fed to dairy cows resulted in significantly lower ammonia release from manure compared with the high CP (15-19%) diets (Frank and Swensson, 2002; Frank et al., 2002). Similar results were reported for feedlot cattle (Cole et al., 2005; Todd et al., 2006). For example, decreasing CP content of finishing cattle diets from 13 to 11.5% reduced daily ammonia flux by 28% (Todd et al., 2006). In summary, reducing CP in beef cattle diets is a practical and cost-effective way to reduce ammonia emissions from feedlots.

Ammonia volatilization is directly related to the proportion of aqueous ammonia (NH_3) in the total ammoniacal-N (NH_4^+ plus NH_3). In general, at constant temperature pH determine the equilibrium between NH_4^+ and NH_3 with a lower pH favoring the ammonium form and hence lower potential of ammonia volatilization. Thus, low urinary pH may be a key factor for reducing ammonia emissions from cattle manure. Various dietary treatments can decrease urinary pH (Stockdale, 2005). Anionic salts (Tucker et al., 1991; Bowman et al., 2003; Mellau et al., 2004) and high fermentable carbohydrates levels (Mellau et al., 2004; Andersen et al., 2004) can reduce urinary pH to below 6.0. In non-ruminants, diet acidification with organic (benzoic) acids (Martin, 1982) or Ca and P salts (Kim et al., 2004) reduced urinary pH and ammonia emissions from pig manure (Canh et al., 1997, Canh et al., 1998a, b).

2. Reduction of Volatile Nitrogen

Ammonia volatilization from manure is predominantly influenced by the concentrations of un-ionized NH_3-N and ionized NH_4^+-N in solution if environmental factors are constant. Therefore, a rational way of reducing ammonia volatilization is to reduce the concentrations of these volatile N species. Five common approaches used to reduce volatile N include: urine-feces segregation, inhibition of urea hydrolysis, pH reduction, binding ammonium, and bioconversion to non-volatile N species.

Urine feces segregation

In general, surplus and inefficient utilization of crude protein or amino acids in livestock diets is the source of N in urine and feces. The majority of N (as much as 97%) is excreted in the form of urea in the urine of cows or pigs and in the forms of organic N in the feces (McCrory and Hobbs, 2001). In a matter of hours to a few days, urea is converted to NH_4^+-N by the enzyme urease, which is found in feces (and in the environment) but not in the urine (Beline et al., 1998). The NH_4^+-N is subject to volatilization from manure depending on pH conditions. In contrast, the breakdown of complex organic N forms in feces occurs more slowly, requiring months or even years to complete. In both cases, N is converted to either NH_4^+-N at low pH or NH_3-N at high pH. This is the basis of the segregation of feces and urine immediately upon excretion of either so that urease enzymes in the feces have reduced contact with the urea in urine. This concept has been tested in two ways. One method uses a conveyor-belt to separate urine and feces, with urine flowing into a pit, while feces left on the belt are conveyed into a separate collection-pit (Lachance et al., 2005; Stewart et al., 2004). The other method drains urine away from feces into a urine-pit immediately after discharge using appropriate floor designs while the feces are then scraped or washed into a separate feces pit (von Bernuth et al., 2005; Swierstra et al., 2001; Braam et al., 1997a; Braam et al., 1997b; Swierstra et al., 1995).

The efficacy of urine-feces segregation in the abatement of ammonia emissions from animal manures is summarized in Table 2. Segregation of urine from feces achieves as much as 99% reduction in ammonia emissions in laboratory studies (Panetta et al., 2004). However, pilot and full-scale urine-feces segregations have been less effective. Several researchers have evaluated a conveyor belt system (Lachance et al., 2005; Stewart et al., 2004). Lachance et al. (2005) compared the performances of three urine-feces separation systems (belt, net, V-shaped scraper) in pig grower-finisher housing. Without the separation process, removing the manure every 2-3 days significantly reduced NH_3 emissions by 46%, compared to the 8-weeks removal in the control. Using the belt or the net and manure removal within a storage period of 2-3 days, the separation of the urine and feces directly under slats resulted in a 49% reduction of NH_3 emissions; this practice was not significantly different from not separating urine and feces. Stewart et al. (2004) also evaluated an inclined conveyor belt used directly as a dunging area in a swine barn. The average ammonia emission in this system was 47% lower than a conventional grower-finisher system with a pit plug design.

Swierstra et al. (2001) investigated pre-cast concrete floors with grooves and a manure scraper in a cow barn. The urine drained along the grooves and through perforations in the grooves spaced about 1 m apart. The perforations were opened and closed to drain urine directly into a slurry pit below and to drain urine at one end of the alley. The feces were scraped to one end of the alley. The floor system was constructed in one compartment of a mechanically ventilated experimental building, while in another compartment, a traditional slatted floor served as a control. Ammonia emissions in the test compartment with open and closed perforations were reduced by 46 and 35% compared with the control compartment.

A similar system utilizing a V-shaped pit floor with an adapted scraper installed beneath the slatted floor of swine pens was evaluated by von Bernuth et al. (2005). Feces on the pit floor slope were scraped to a collection point after the liquid, including urine, had drained to a holding tank via a central pipe. Ambient ammonia concentration did not exceed 7.5 ppm in the pens throughout the monitoring period. Braam et al. (1997a) evaluated mitigation of ammonia emission from similar V-shaped solid floors with a gutter at the bottom of the V-groove to drain urine in cow houses, with and without water spraying. Ammonia emission from the system without spraying water was reduced by 50% on average compared with a control. In addition, ammonia emission was further reduced by an average of 65% when water was sprayed at a rate of $6l\ d^{-1}\ cow^{-1}$ after scraping with a frequency of 12 times per day. Work by Swierstra et al. (1995) evaluated a slatted floor versus a solid sloping floor with a central gutter with or without a finish in cow barn. The emissions from inclined solid floors were about 50% of the emission of the conventional slatted floors, and floor finishes did not statistically affect the emissions.

A similar study by Braam et al. (1997b) also evaluated a traditional slatted floor and two solid floor systems; one of the latter was sloped (3%) and drained urine in a urine-gutter while the other was not inclined at all. Both the solid floors were either highly scraped (96 times a day) or normally scraped (12 times a day). The non-sloped solid floor scraped normally had the same ammonia emission as the slatted floor, while the sloped solid floor also normally scraped, further reduced ammonia emission by 21% over the other two systems. Increasing scraping to 96 from 12 times/day decreased ammonia emission by only a marginal 5%, which may not economically justify the extra scraping efforts.

All the urine-feces segregation methods evaluated and reviewed in this article reduced ammonia emissions from livestock barns by about 50% compared to the conventional manure handling systems (mixed urine-feces systems). In addition, some limited flushing after feces scraping from the sloped floors further significantly reduce ammonia emissions. In conclusion, the critical factors that need to be considered in the choice of the method for separating urine from feces are the cost of installing the system, maintenance, and ease versus cost of operation.

Table 2 - Summary of ammonia emissions reduction from manure storages using urine-feces segregation

Animal Species	Segregation method	Emissions reduction (%)	References
Swine	Laboratory studies	99	Panetta et al., 2004
Swine	Conveyor belt	47-49	Lachance et al., 2005; Stewart et al., 2004
Cattle	Pre-cast grooves in concrete floor	46	Swierstra et al., 2001
Cattle	V-shaped pit floor with gutter at the V	50-65	Braam et al., 1997a
Cattle	Sloped (3%) solid floor	21	Braam et al., 1997b

Urease inhibitors

The enzyme urease found in the feces rapidly hydrolyzes urea and uric acid into NH_4^+-N when urine mixes with feces (Beline et al., 1998). However, urease inhibitors can block this urea hydrolysis and reduce ammonia emissions from the manure (Varel, 1997; Varel et al.; 1999; Parker et al., 2005).

In laboratory experiments, two urease inhibitors; cyclohexylphosphoric triamide (CHPT) and phenyl phosphorodiamidate (PPDA), successfully controlled urea hydrolysis in typical cattle and swine slurries (Varel, 1997). At dosages of 10 mg/*l*, both inhibitors stopped the hydrolysis of urea in cattle waste and swine waste for 4 to 11 days. In contrast, hydrolysis of urea in untreated cattle or swine waste (control) was complete within one day. Weekly addition of the inhibitors was the most effective method of preventing urea hydrolysis. Weekly additions of 10, 40, and 100 mg of PPDA per liter of cattle waste (5-6 g urea L^{-1}) prevented 38, 48, and 70% of the urea, respectively, from being hydrolyzed during a period of 28 days. For the swine waste (2·5 g urea L^{-1}), the same PPDA concentrations prevented 72, 92, and 92%, respectively, of the urea from being hydrolyzed during the same study period. The results of these experiments provide technical strategies for significant control of ammonia emissions from livestock facilities while increasing the fertilizer value of these resources by improving the N:P ratio.

Another laboratory study was conducted to evaluate the effect of rate and frequency of urease inhibitor application on ammonia emissions from simulated beef cattle feed-yard manure surfaces (Parker et al., 2005). The urease inhibitor N-(n-butyl) thiophosphoric triamide (NBPT) was applied at rates of 0, 1, and 2 kg ha^{-1}, at 8, 16, and 32 day frequencies, and with or without simulated rainfall. Synthetic urine was added every two days to the manure surface. This urease inhibitor applied every 8 days was most effective, with the 1 and 2 kg NBPT ha^{-1} treatments resulting in 49% to 69% reduction in ammonia emission rates, respectively. According to the authors, the 8-day, 1 kg NBPT ha^{-1} treatments had the most promising benefit/cost ratios, ranging between 0.48 and 0.60. Although the technical and economic potentials of use of NBPT for reducing ammonia emissions in beef cattle feed yard was demonstrated, the authors cautioned that because of possible buildup of urea in the pen surfaces, higher NBPT application rates may be necessary with time. In an earlier study, Varel et al. (1999) reported accumulation of urea, less concentration of ammonia, and more concentrations of total-N in cattle feedlot manure when 20 mg[NBPT]/kg of manure was applied weekly for six weeks compared with control. Panetta et al. (2004) reported contradictory results when NBPT was applied to swine slurry in laboratory studies. In these laboratory studies, additions of single (76 μ*l*/*l*) and double (152 μ*l*/*l*) dosages of NBPT increased ammonia emissions by 50 and 140% compared with the control.

Although use of urease inhibitors seems promising in the laboratory studies, no case studies were found in the literature on the use of these additives in the control of ammonia emissions in full-scale concentrated animal feeding operations (CAFOs). The lack of adoption of urease inhibitors may be attributed to the unknown effects of these chemicals on the crops or pastures where the manure is eventually applied as fertilizer.

pH reduction

Ammonia volatilization is directly proportional to the proportion of un-ionized aqueous NH_3-N in the TAN. When temperature is held constant, pH determines the equilibrium between NH_4^+-N and NH_3-N in aqueous systems. A lower pH leads to a lower proportion of NH_3-N and, therefore, to a lower potential of ammonia volatilization. Acidification of animal manure for mitigation of ammonia loss relies on this basic principle. The greatest increase in ammonia release takes place between a pH of 7 and 10: below pH 7 ammonia volatilization decreases, and at a pH of about 4.5, there is almost no measurable free ammonia (Hartung and Phillips, 1994).

Past studies have clearly demonstrated the efficacy of pH reduction in the mitigation of ammonia volatilization from livestock manure. The results of these studies are summarized in Table 3. Acidification of pig and cattle slurries using H_2SO_4 from a pH of 8 to a pH of 1.6 reduced ammonia emissions progressively and completely stopped ammonia volatilization at a pH of 5 in pig slurries and at a pH of 4 in cattle slurries (Molloy and Tunney, 1983). Jensen (2002) maintained a pH of 5.5 using H_2SO_4 in swine manure in full-scale swine-confinement buildings with a slatted floor and under-the-floor manure pit. These researchers reported reduction of ambient concentrations of the ammonia by about 75 to 90%, while pigs weight increased by 1074 g/day during the study period compared to the pigs in the control buildings.

In a similar study, Stevens et al. (1989) used H_2SO_4 to acidify cow and pig slurries to a pH of 5.5 and 6.0. At these cow and pig slurries pH-conditions, ammonia volatilization were effectively reduced by 95% in the lab and by 82% in the field. Similar studies (Frost et al., 1990) using sulfuric acid to acidify whole cattle slurry to a pH of 5.5 reduced ammonia volatilization by 85%. Al-Kanani et al. (1992) similarly reported ammonia loss reduction of 75% when sulfuric acid was applied to swine manure in laboratory experiments. Somewhat lower ammonia reductions (14-57%) were reported by Pain et al. (1990) when sulfuric acid was used to lower the pH of cattle slurry to about 5.5. Husted et al. (1991) investigated use of another strong acid (hydrochloric acid) on the acidification of stored cattle slurry, and noted that the addition of 240 meq HCl/*l* resulted in a reduction of the potential ammonia loss by as much as 90% compared to the control. Safley et al. (1983) reported about 50% reduction in ammonia loss using phosphoric acid within 28 days of dairy cattle manure storage. Al-Kanani et al. (1992) reported significantly more (about 90%) ammonia loss reduction using the same phosphoric acid on swine manure. Phosphoric acid, however, adds P concentration in the manure, which is undesirable. Some of the weaker acids like propionic and lactic acids are as effective as the strong acids, and have been observed to reduce ammonia emissions by as much as 90% when pH of the manure is maintained at 4.5 (Parkhust et al., 1974).

Other researchers have investigated use of other acidifying additives (aluminium potassium sulfate or alum, ferric chloride, sodium hydrogen sulfate, and calcium chloride) for mitigation of ammonia emissions from livestock manure (Li et al., 2006; Armstrong et al., 2003; Shi et al., 2001; Kithome et al., 1999; Al-Kanani et al., 1992; Husted et al., 1991; Witter and Kirchmann, 1989a; Mackenzie and Tomar, 1987; Molloy and Tunney, 1983). Although most of the additives effectively reduce pH, they are generally not as effective in reducing ammonia loss as the strong acids because they cannot maintain stable pH conditions like their counterparts.

Li et al. (2006) reported 89% reduction in ammonia volatilization when alum was applied at the rate of 2 kg[liquid aluminum sulfate]/m^2[surface area]. Armstrong et al. (2003) observed that application of liquid alum equivalent of 45, 90, and 135 kg[aluminum sulfate]/93 m^2 of broiler litter surface was effective at maintaining in-house ammonia concentrations at below 25 ppm for two weeks, three weeks, and three weeks of the grow-out, respectively. Shi et al. (2001) investigated the efficacy of alum on beef cattle manure. Compared to the control, ammonia emissions reduction during 21 days of monitoring were 91.5% at 4500 kg/ha alum and 98.3% at 9000 kg/ha alum. The advantage of alum use in the reduction of ammonia emissions is reduction of soluble phosphorus and the potential for phosphorus runoff or leaching.

The investigations of Witter and Kirchmann (1989a) on the efficacy of calcium and magnesium salts on ammonia loss during aerobic treatment revealed efficiencies of most of these salts ranged between 85-100% efficient within 2-3 weeks and between 23-52% by the seventh week of incubation. Shi et al. (2001) evaluated the efficacy of $CaCl_2$ on reducing ammonia emissions from beef cattle manure in the laboratory. Compared to the control, ammonia emissions 21 days after application were reduced by 71.2 and 77.5% at 4500 and 900 kg/ha $CaCl_2$ application. Calcium chloride was less effective than alum at the same application rates. Witter (1991) examined ammonia volatilization after the addition of $CaCl_2$ to fresh and anaerobically stored manure before land application of the respective slurries. Within 48 h after application, $CaCl_2$ reduced ammonia loss by 73 in the fresh manure and by 8% in the anaerobically digested manure. Kithome et al. (1999) reported a 10% decrease in ammonia volatilization at the addition of 20% $CaCl_2$ to poultry manure. This is similar to the maximum 15% ammonia reduction reported by Husted et al. (1991) achieved by addition of 300-400 meq/l of $CaCl_2$ to cattle slurry. This product is thus only suitable for reducing ammonia in poultry housing, and may not be suitable for reducing ammonia loss from land applied slurries previously stored anaerobically. Al-Kanani et al. (1992) reported a significant reduction in pH and ammonia emission (87%) when monocalcium phosphate monohydrate (MCPM) was applied to cattle manure. Mackenzie and Tomar (1987) also investigated addition of MCPM to liquid hog manure with and without aeration. A decrease in pH was observed with addition MCPM, but the pH increased when addition of the salt addition ceased. During subsequent aeration, total nitrogen (TN) decreased significantly in the control manure, while no significant change was observed in the TN in the manure with MCPM.

Overall, strong acids tested for reducing slurry pH are more cost-effective than the weaker acids and acidifying salts, but are more hazardous for use on the farm than the latter. Therefore, although the acidifying salts and other weaker acids may be less effective than strong acids, they are non-hazardous and relatively low cost; which increases their suitability for on-farm use.

Table 3 - Summary of ammonia emissions reduction from manure storages by lowering pH

Animal Species	Agent or substance	Emissions reduction (%)	References
Cattle and pig	Sulfuric acid	14-100	Molloy and Tunney, 1993; Jensen, 2002; Stevens et al., 1989; Frost et al., 1990; Al-Kanani et al., 1992; Pain et al., 1990
Cattle	Hydrochloric acid	90	Husted et al., 1991;
Cattle and pig	Phosphoric acid	50	Safley et al., 1983
Pig	Phosphoric acid	90	Al-Kanani et al., 1992
Broiler	Alum	89	Li et al., 2006;
Cattle	Alum	91-98	Shi et al., 2001
Cattle	Calcium chloride	71-78	Shi et al., 2001; Witter, 1991
Poultry and cattle	Calcium chloride	10-15	Kithome et al., 1999; Husted et al., 1991;
Cattle	Monocalcium phosphate monohydrate	87	Al-Kanani et al., 1992

Ammonium binding

This category of substances have a high affinity for holding onto NH_4^+ ions thus reducing ammonia volatilization through decreased concentration of free NH_4^+ ions. The methods of ammonia binding in some cases are not well understood. A summary of the performance of these substances is provided in Table 4.

Zeolite is a cation-exchange material with a high affinity and selectivity for NH_4^+ ions due to its crystalline-hydrated properties resulting from its infinite 3-dimentional structure (Mumpton and Fishman, 1977). A layer of 38% zeolite placed on the surface of composting poultry manure reduced NH_3 losses by 44% (Kithome et al., 1999). An earlier study by Witter and Kirchamann (1989b) investigating the efficacy of zeolite on the reduction of ammonia loss from poultry manure during aerobic incubation reported an insignificant 1.5% reduction in ammonia loss when mixed with manure in the ratio of 1:4. Nakaue et al. (1981) observed a reduction of up to 35% ammonia loss by the addition of 5 kg/m^2 of zeolite to broiler litter. Portejoie et al. (2003) investigated reduction of ammonia loss in pig manure during storage and land application using zeolite, and reported a 71% reduction in ammonia emissions. Li et al. (2006) evaluated the efficacy of zeolite in reducing ammonia emissions from fresh poultry manure in laboratory experiments. Application of typical medium rates of 5% (w/w) zeolite reduced ammonia emission by 81%. Zeolite seems to be more effective for reduction of ammonia in animal slurries and liquid manures than in the solid poultry manures.

Two other additives in this category evaluated for abatement of ammonia emissions in livestock manures are Sphagnum peat moss (*Sphagnum fuscum* peat) and yucca plant extracts (saponins). Al-Kanani et al. (1992) compared the efficacy of several amendments on liquid hog manure and concluded that Sphagnum peat moss was just as effective as the strong acids (reduced ammonia volatilization by as much as 99%), although it did not drop the pH to the same levels as the acids. Barrington and Moreno (1995) observed that a 2-cm cover of floating Sphagnum reduced ammonia loss by as much as 80%. Similar results were reported by other researchers (Al-Kanani et al., 1992), but Witter and Kirchamann (1989b) reported a somewhat lower (24%) reduction in ammonia emissions when sphagnum peat, mixed in the ratio of 1:4, was used in poultry manure during aerobic incubation. This product also seems to be more effective on the animal slurries than on the solid poultry manure in the same way as zeolite. Kemme et al. (1993) reported ammonia loss reduction of 23% when saponins were applied to pig slurries. Panetta et al. (2004) reports similar results when these extracts were applied to swine slurry in laboratory studies. In this category, saponins do not seem to be as effective in mitigating ammonia emissions as either zeolite or peat moss.

A host of other additives hidden in brand names, presumably to protect commercial interests of their inventors have also been evaluated. Heber et al. (2000) evaluated a commercial manure additive (Alliance®) developed by Monsato EnvironChem (St. Louis, MO.) to improve air quality in swine buildings. Alliance® was sprayed into the manure stored in pits underneath slatted floors. Compared to the control, this additive reduced ammonia emissions by 24%, but also further diluted the manure by 20%. The authors estimated the cost of this additive at $1.38/pig space per year or $0.50/marketed hog based on 135-day growth cycles, and a product cost of $3.43/*l*, and noted that because of the modest reduction in ammonia emission, this additive may not be cost-effective to most producers. Amon et al. (1997) compared the effectiveness of another commercial additive (De-Odorase®) to a control (no additive) in broiler production. This product (De-Odorase®) significantly reduced ammonia emission by 50% over the control. It is important for producers to ensure effectiveness of the respective additives has been scientifically verified by independent and reputable institutions before they adopt them for use in their facilities.

In summary, amongst ammonia binders, zeolite seems to be more effective for reduction of ammonia emissions from animal slurries and liquid manures than in solid poultry manures. Sphagnum, like zeolite, also seems to be more effective on the animal slurries than on the solid poultry manure. Saponins do not appear to be as effective in mitigating ammonia emissions as either zeolite or peat moss. In general, large quantities of these additives are required, and in most cases (with additives such as the acid/acidic salts); precautions must be taken to safeguard the safety of livestock and farm workers. In addition use of acids may result not only in an undesirable increase in the mineral content of the manure/litter, but also in the corrosion of equipment and structures. It is important to determine appropriate application methods to ensure these additives are most effective.

Table 4 - Summary of ammonia emissions reduction from manure storages using ammonium binders

Animal Species	Binding Agent	Emissions reduction (%)	References
Poultry	Zeolite	1.5-96	Kithome et al., 1999; Witter & Kirchamann, 1989b; Nakaue et al., 1981; & Li et al., 2006
Pig	Zeolite	71	Portejoie et al., 2003
Pig	Sphagnum peat moss	80-99	Al-Kanani et al., 1992; & Barrington and Moreno, 1995
Poultry	Sphagnum peat moss	24	Witter & Kirchamann, 1989b
Pig	Saponins (yucca extract)	23	Kemme et al., 1993
Pig	Alliance®	24	Heber et al., 2000
Poultry	De-Odorase®	50	Amon et al., 1997

Biological treatments

Biological treatments processes are either based on assimilation and immobilization of volatile N or transformation of volatile N into non-volatile inorganic N. The former approaches are geared toward recovering N products from liquid animal waste and include production of: single cell proteins; amino acids; and protein rich aquaculture plants such as duckweed and algae. These alternatives systems will not be reviewed in this article. Transformation of volatile N species to non-volatile species is a major biological treatment process comprising of coupled nitrification and denitrification processes. However, most treatments employ some variation of physical, chemical or components of both physical and chemical unit processes to provide suitable conditions for these processes to occur efficiently and cost-effectively. During nitrification, nitrifying bacteria transforms ammonia to oxidized N (nitrite and nitrate). These compounds are then biologically reduced to environmentally benign N gas (N_2) by denitrifying bacteria. The reaction rate of nitrification is extremely low compared to that of denitrification; consequently, nitrification is the rate-limiting step. Nitrificication is the more critical step, and usually receives more attention in biological treatment of wastewaters for removal of ammonia. Common biological treatment systems consist of either single or two bioreactors. The single-reactor-systems are either run alternately in aerobic and anaerobic modes, or have both aerobic and anoxic zones in the same reactor to effect nitrification and denitrification, respectively. In contrast, these processes take place in separate reactors in the two-reactors-systems. To enhance the nitrification kinetics in particular, other features such as cell immobilization on inert materials or other methods of biomass enrichment are incorporated.

Hu et al. (2003) studied a continuous-flow intermittent aeration (IA) process for N removal from anaerobically pre-treated swine wastewater at the laboratory scale. In this study, experiments were conducted at different: influent COD concentrations, aeration:no-aeration ratios, hydraulic retention time (HRT), and solids retention time (SRT). At the HRT of 3 days and SRT of 20 days in the IA tanks, nitrification and denitrification were successfully achieved in the IA process. Nitrogen removal rates surpassed 80%, and nitrite and nitrate were less than 20 mg/*l* in the effluents. A similar system was evaluated by Zhang et al. (2006) for treating swine manure rich in N. In this study, a bench-scale sequencing batch reactor (SBR) was ran in a cyclic anaerobic-anoxic mode using low-intensity aeration of 1.0 L[air] m^{-3} [wastewater] s^{-1}, coupled with two-step influent feeding.

Approximately 97.5% of the TN in the treated manure was removed, with only 15 mg N/*l* of the oxidized N (NO_3^+-N) left in the effluent. Luostarinen et al. (2006) evaluated a single-moving bed bioreactor (MBBR) for treatment of anaerobically pre-treated dairy parlor wastewater and a mixture of kitchen waste and black water. The effect of intermittent aeration and continuous versus sequencing batch operation was also studied. The MBBRs removed 50–60% of N irrespective of the operational mode. Complete nitrification was achieved, but denitrification was impeded by insufficient carbon. The range of N removal in this study was, however, much lower compared with the rates reported by Hu et al. (2003) and Zhang et al. (2006). A likely explanation for these discrepancies may be due to the differences in the influent wastewaters. Loustarinen's studies used milking parlor wastewater, while Hu et al. (2003) and Zhang et al. (2006) systems were run on swine wastewater. Another likely explanation is the confusion in the reporting of N (either as TN, TKN, or TAN).

Pan and Drapcho (2001) reported on a continuous-flow two-reactor (anoxic and aerobic) system for treatment of swine wastewater. The aerobic reactor was maintained at 5mg/*l* dissolved oxygen. This system was run at HRT of 35 hours in the anoxic and 36 hours in the aerobic, and a recirculation ratio of 1.0. At steady state, ammonia in the effluent was reduced by about 85%, of which 51% was retained as nitrate in the effluent. A similar bench-scale system was evaluated by Ten-Have et al. (1994) for treatment of supernatant from settled sow-manure. This system consisted of separate reactors for nitrification and denitrification and a recycle of mixed liquor from former to the latter. More than 99% of the ammonia was converted to nitrate. Complete denitrification was not accomplished because of inadequate fermentable carbon in the manure supernatant. Molasses was added to provide the extra carbon needed. Shin et al. (2005) investigated a slightly different two-reactor system for biological removal of N from swine wastewater rich in organic matter and N. This system consisted of a submerged membrane bioreactor (MBR) for nitrification followed by an anaerobic upflow bed filter (AUBF) reactor for denitrification. Total N removal efficiency of 60% was achieved at an internal recycle ratio of three times flow-rate. Complete nitrification of the ammoniacal-N was achieved in the process.

Vanotti and Hunt (2000) evaluated an immobilized-cell (encapsulated in polymer resin) system for enhanced nitrification of ammonia in swine wastewater. This system was evaluated for treatment of high-strength swine lagoon wastewaters containing about 230 mg [NH_4-N]/*l* and 195 mg [BOD_5]/*l*. A culture of acclimated lagoon nitrifying sludge immobilized in 3 to 5 mm polyvinyl alcohol polymer pellets was used for this experiment. Alkalinity was maintained with inorganic carbon to ensure a liquid pH within the optimum range (7.7-8.4). In batch treatment, only 14 h were needed for nitrification of NH_4^+-N. In contrast, it took 10 d for a control (no-pellets) aerated reactor to start nitrification, while as much as 70% ammonia was lost via air stripping. In continuous flow treatment, nitrification efficiencies of 95% were obtained with NH_4^+-N loading rates of 418 mg[N] l^{-1} [reactor] day^{-1} at 12 h HRT. In all cases, the NH_4^+-N removed was entirely recovered in oxidized N forms. The immobilized-cell technology thus further enhanced ammonia removal from anaerobic swine lagoons wastewater.

An 8 m^3/day pilot scale two-reactor system was evaluated by Westerman et al. (2000) for treatment of supernatant from settled flushed swine wastewater. The main system consisted of two upflow aerated biofilters connected in series. The aerated biofilters ran at around 27°C, removed about 84% of the TKN, 94% of the TAN, and 61% of the TN. A significant portion of the NH_3-N was converted to nitrite plus nitrate nitrogen (NO_2+NO_3-N). The TKN, TAN, and TN removal averaged 49%, 52%, and 29%, respectively, when the reactors were ran at around 10^{o}C. The unaccounted N of about 24% could have been lost through ammonia volatilization or through denitrification within the biofilm. Westerman and Bicudo (2002) later evaluated a full-scale nitrification/denitrification system for biological treatment of flushed swine manure in a 3000 finishing-swine facility. The system consisted of a pond with a mixing zone for denitrification (anoxic), and an aeration zone for nitrification, with recirculation from aeration zone to mixing zone, and a recycle from aeration zone to the barns for flushing. Nitrogen reduction in the effluent was 65 to 90%, with more than 90% of the N being in inorganic N form. In addition, significant reduction in odor perception, irritation, and unpleasantness from liquid samples drawn from the treatment system was reported. The report also noted the high energy cost for operation. Another full-scale nitrification-denitrification system is reported by Townsend et al. (2003). This system was constructed to serve 52,800 grow-finish pigs. Nitrification and denitrification occurred in a single wastewater treatment plant centrally located on the farm. Effective TN reduction averaged about 87%. Townsend et al. (2003) also reported significant foam generation during aeration, necessitating continuous use of a defoaming agent for the treatment to continue.

When designed and ran appropriately, these systems can effectively (up to 99%) mitigate ammonia emissions in CAFOs. It appears that the major hindrance is the economics of installing and operating the systems. An important element of biological N removal is the carbon source to complete the denitrification process. Reporting of N (either as TN, TKN or TAN) needs to be well defined to enable inter-comparisons.

3. Building Designs and Manure Managements

Accumulated urine and feces on the floor is the main source of ammonia volatilization within the buildings. The longer their residence times on the floor, the more the ammonia volatilization. The manure can be also thinly spread-out, which further exacerbates ammonia volatilization as this provides larger surface areas. Frequent removal of manure may be critical in mitigating ammonia volatilization within the building. Scraping, flushing, slatted floors, conveyor belts or combinations of these systems are currently the most common methods of removing manures from the floors or buildings.

Flushing floors with water achieved a 14 to 70% reduction in ammonia loss compared to use of slatted floors in dairy barns (Voorburg and Kroodsma, 1992; Kroodsma et al., 1993; Ogink and Kroodsma, 1996). Increasing flushing frequency, increasing the amount of water, and use of fresh water (as opposed to recycled water) further reduce ammonia volatilization within the building (Voorburg and Kroodsma, 1992). However, since these practices may also increase both the volume of the slurry to be handled and the cost of slurry utilization, a compromise between flushing frequency, amount of water, use of fresh water and the respective additional reduction of ammonia losses has to be established.

Kroodsma et al. (1993) investigated the effects of different manure managements on ammonia emissions from freestall dairy houses. Manure scraping did not significantly decrease ammonia emissions, while flushing with water decreased the emissions by up to 70%. Frequent flushing over short periods was more effective than prolonged, but less-frequent flushing. Ogink and Kroodsma (1996) evaluated two cattle manure management systems for reduction of ammonia emissions from cow houses with partially slatted floors. One method was based on scraping the slats and subsequent flushing with water every 2 h, using 20 L[water] d^{-1} cow^{-1}. The second method was similar, except that 4 g of formalin per liter of flushing water was added. Compared to a control (no scraping or flushing), the former method only lowered the emission by 14%, while adding formalin to the flushing water reduced emissions by 50%. Misselbrook et al. (2006) reported that pressure washing and the use of a urease inhibitor in addition to yard scraping were more effective means of reducing emissions compared with yard scraping alone, while reduction of yard area per animal was also an effective strategy to reduce total emissions.

In slatted floor systems, the frequency of manure removal from the pits under the slats is critical in the management of ammonia emissions within the building (Hartung and Phillips, 1994). Hartung and Phillips (1994) compared four different manure removal strategies: a partially slatted floor (PSF) with a slurry pit emptied every two weeks, a PSF with a sloped slurry channel beneath that is flushed several times a day, a PSF floor with a continuous recirculatory flushing, and a PSF floor with a continuous recirculatory flushing combined with basin and plug. The control was a PSF with slurry pit underneath providing storage for six months. Respective ammonia volatilizations were 20, 60, 40, and 80% less than in the control. In a similar study, Lachance et al. (2005) reported a significant 46% reduction in ammonia emissions when manure was removed every 2-3 days, compared to eight weeks removal frequency in the control. Lim et al. (2004) evaluated several manure management strategies on reduction of ammonia emissions in confined finishing pigs. The strategies included daily flushing, and static pits with 7, 14, and 42 d manure accumulation cycles, with and without pit recharge, with some secondary lagoon effluent after emptying. Flushing and static pit recharge with lagoon effluent resulted in significantly less NH_3. Mean NH_3 emission rates were 15, 27, and 25g d^{-1} AU^{-1} for the 1, 7, and 14 d cycles without pit recharge, and 10, 12, and 11 g d^{-1} AU^{-1} for the 7, 14, and 42 d cycles with pit recharge, respectively. Mean daily NH_3 emissions from the rooms with static pits were 51 to 62% lower with recharge than without recharge. In summary, less NH_3 emissions occurred when pits were recharged after emptying, and when pits were emptied more frequently.

In poultry buildings (cage) removing manure twice a week using belts, or weekly with drying manure on belts reduced NH_3 emission from battery cage houses by 60% or more compared to allowing manure stay on the belt. However, daily removal has the potential of further reducing NH_3 emissions, since hardly any degradation then takes place inside the house (Cowell and Apsimon, 1998).

Ammonia volatilization within the buildings is also a function of the building ventilation system. Ventilation would increase NH_3 losses because of reduced resistance to NH_3 transfer into the air above the manure. For example, a common practice to reduce elevated NH_3 levels in poultry houses is to increase ventilation rates above the values needed for proper litter moisture control. The increased ventilation rates reduce NH_3 concentration in the house, but translate directly into higher NH_3 emissions as well into costs of running the fans.

4. Emissions capture and treatment

Important mitigation strategies of ammonia and other gaseous emissions involve capturing or trapping the fugitive gases and subsequent treatment of the respective captured emissions. These strategies can be put into two broad categories: (i) filtration and biofiltration, and (ii) use of permeable and impermeable covers.

Filtration and biofiltration

Filtration is more of a physical-chemical process while biofiltration not only traps but also biologically degrades or converts trapped compounds into their benign forms. Removing NH_3 from vented air using filters or scrubbers (water and acid) is feasible where barns are mechanically ventilated (Sommer and Hutchings, 1995; Groot Koerkamp, 1994). In most cases, the practical applications of these cleaning devices are limited due to their relatively high cost and technical problems due to dust, especially in poultry and swine houses.

Sun et al. (2000) describes a 20-cm deep biofilter consisting of a mixture of compost and wood chips tested for removal of NH_3 from swine housing ventilation air. On average, this system removed 83% of ammonia in the carrier air at biofilter moisture content of 50% at a retention time of 20s. Tanaka et al. (2003) also reported a reduction of 94% in ammonia from composting air in a biofilter consisting of finished compost (of cattle manure and sawdust) within the first 72h of treatment. Hong and Park (2005) reported 100% ammonia removal efficiency from air from a composting pile (of dairy manure mixed with crop residues) in a 50-cm deep, 50:50 manure compost to coconut peels biofilter. Sheridan et al. (2002) evaluated a pilot scale wood chip biofilter for reducing ammonia from exhaust air from a pig finishing building. A 50 cm deep biofilter made from 20 mm screen size wood chips efficiently removed between 54 and 93% ammonia depending on volumetric loading rate. A filter bed moisture level of 63% or greater was recommended to maintain the biofilter efficiency. A biofilter consisting of a mixture of pine and perlite removed 95.6% ammonia from ventilation air from a swine facility in a pilot-scale system (Chang et al., 2004). Kastner et al. (2004) reported that a biofilter made of pre-screened yard waste compost reduced ammonia by 25 to 95% in ventilation air from a modern 2400-sow farrow-to-wean unit, depending on residence time and inlet ammonia concentration. Martinec et al. (2001.) evaluated several biofilter materials (biochips, coconut peels, bark-wood, pellets+bark, and compost) for reduction of ammonia from swine operations. Ammonia reduction with these materials ranged between 9 and 26%.

There is a broad range of biofilter efficiencies in the removal of ammonia in carrier-air. The wide range of performances (9-100%) reported in the literature may be attributed not only to the wide range of biofilter-materials, but also on other factors such as maintenance of optimum moisture in the filter bed, the residence time of the air in the biofilter (Sun et al., 2000; Hartung et al., 2001; Tanaka et al., 2003), the ammonia load in the incoming air (Sheridan et al., 2002; Kastner et al., 2004), and how well the microbial community is established in the biofilter. Properly designed and ran systems can effectively mitigate ammonia emissions from livestock operations.

For the readers interested in more details on acid scrubbers and trickling filters, a comprehensive review of these technologies for treatment of exhaust air from pig and poultry houses in the Netherlands has recently been completed (Melse and Ogink, 2005). In that review article, ammonia removal in acid scrubbers ranged from 40 to 100%, with an overall average of 96%, while ammonia removal efficiency in biotrickling filters ranged from -8 to +100% with an overall average of 70%. Process control with pH and automatic water discharge were sufficient to guarantee ammonia removal efficiency in acid scrubbers. The review concluded that improvement of process control is required in biotrickling filters to guarantee ammonia removal efficiency. Recent results (Kosch et al., 2005) are similar to values found the review paper.

Impermeable and permeable covers

The simplest control method to mitigate ammonia emissions from storage and treatment systems open to the atmosphere is to use a physical cover to contain the emissions. Impermeable covers, which trap gases released from such systems, are regularly used in conjunction with scrubbers or biofilters. The effectiveness of these covers depends not only on their trapping efficiency, but also on the effectiveness of the scrubber or the biofilter with which they are used in combination. Permeable covers trap and bio-transform ammonia just like biofilters, and include materials such as straw, cornstalks, peat moss, foam, geotextile fabric, and Leca® rock. The performances of impermeable and permeable covers are summarized in Table 5.

In comparison to an uncovered control, two impermeable covers; a floating film (two 2-mm thick polyethylene film layers glued together) and a tarpaulin, effectively reduced ammonia emissions from swine manure lagoons by 99.7 and 99.5%, respectively (Funk et al., 2004). Scotford and Williams (2001) reported nearly 100% ammonia reduction from a pig slurry lagoon covered with a floating 0.5-mm thick reinforced ultraviolet light-stabilized opaque polyethylene cover. Funk et al. (2004) reported effective control of ammonia emission using an air-supported 0.35-mm vinyl coated fabric cover installed on an earthen-embanked swine lagoon, but experienced major challenges in controlling the gas leakage. Ammoniacal-N is not soluble in oil; therefore, thin layers of oil (oil-films) can also create impermeable covers over stored manure slurries. Heber et al. (2005) evaluated the efficacy of soybean oil sprinkling on ammonia emission mitigation in tunnel-ventilated swine finishing barns. The oil treated barn resulted in 40% less NH_3 emission than the control barn. Better results have been reported when a layer of vegetable oil was placed on the surface of manure liquid/slurry. Guarino et al. (2006) reported a reduction of ammonia emissions between 79 and 100% when 3 and 9-mm layers of vegetable oil were applied on stored pig and cattle slurries. Portejoie et al. (2003) reported similar ammonia emission reductions (93%) with a 10-mm oil layer. Other laboratory and on-farm studies with a 6 mm rapeseed oil layer indicated control of ammonia emissions by up to 85%, while a thinner 3-mm layer was ineffective (Hornig et al., 1999).

A permeable geotextile cover installed on swine manure storages resulted in 44% reductions in NH_3 emissions, but the cover performance deteriorated after one year (Bicudo et al., 2004). Clanton et al. (2001) reported 37, 72, and 86% reduction in ammonia emissions from swine manure storage with 10, 20, and 30 cm-thick straw covers, respectively, supported on a geotextile fabric. The permeable geotextile fabric itself did not have significant effect on ammonia emissions without a straw layer. Compared to uncovered cattle and pig slurry, surface crust, peat, straw, PVC foil, and Leca® rock achieved 24, 32, 60, 26, and 14% maximum ammonia emission reductions, respectively (Sommer et al., 1993). Zahn et al. (2001) reported a 54% reduction of ammonia emissions from a lagoon covered with an acclimated proprietary polymer composite bio-cover. Relative to an uncovered control, Hornig et al. (1999) reported ammonia emissions reduction of 80 to 91% with straw and Pegulit (a natural mineral buoyant material) covers. Development of a surface crust in stored cattle manure was as effective as a 15 cm layer of straw, and reduced ammonia emissions by as much as 20% (Sommer et al., 1993). Guarino et al. (2006) reported effective ammonia reduction from pig and cattle slurry with adequate cover thickness of wheat straw, wood chips, and corn stalks. With 14 cm thick straw, wood chips, and corn stalks covers, ammonia emissions reductions were 100, 91, and 60%, respectively. However, by using 7 cm thick covers, the respective ammonia reductions were only 59, 17, and 37%. In laboratory studies, Xue et al. (1999) reported that 5 to 10 cm straw covers reduced ammonia emissions by 90% from dairy manure storages. Miner and Pan (1995) reported permeable covers configured with straw, zeolite, or a combination of both, effectively reduced ammonia emissions by 90% from manure storages. A permeable polystyrene foam cover was reported to reduce ammonia emissions by 45 to 95% in manure storages (Miner and Suh, 1997). In other laboratory and field studies, Miner et al. (2003) reported ammonia reductions from swine slurries of about 80% using a 5 cm thick permeable polyethylene foam lagoon cover. Balsari et al. (2006) evaluated a low cost cover (Leca® balls layer) for ammonia emission abatement from swine slurry storage and observed a significant ammonia reduction (up to 87%) with a 10 cm layer of Leca® balls.

Impermeable covers are generally more effective (up to 100%) than permeable covers in ammonia mitigation strategies from manure storages. However, costs for covers vary widely depending on the material used and the method of application. The length of the time the covers will be in place is an important consideration. Removal and clean-up of the material left behind when the useful life of the covers is over is equally important. In addition, if no biofilters are used to clean up the trapped gases under impermeable covers, excessive ammonia and other gaseous emissions may occur during land application. Massey et al. (2003) evaluated the economics of installing impermeable lagoon covers on swine farms, and showed that at \$0.72 to \$3.41/cwt of hog marketed, the initial purchase price of the cover was the biggest hurdle. The second major hurdle is the availability of more land base to receive the conserved N, which could be about 3.5 times larger than open lagoons.

Table 5 - Summary of the performances of permeable and impermeable covers in abating ammonia emissions from livestock manure storages

Cover Type (s)	Emissions reduction (%)	References
Polyethylene	80-100	Funk et al., 2004; Scotford and Williams, 2001; Miner et al., 2003
Tarpaulin	99.5	Funk et al., 2004
Oil films	40-100	Heber et al., 2005; Guarino et al., 2006; Portejoie et al., 2003; Hornig et al., 1999
Geotextile cover	44	Bicudo et al., 2004
Straw covers	37-90	Clanton et al., 2001; Sommer et al., 1993; Horning et al., 1999; Guarino et al., 2006; Xue et al., 1999; Miner & Pan, 1995
Surface crust, peat, & PVC foil	24-32	Sommer et al., 1993;
Leca rock	14-87	Sommer et al., 1993; Balsari et al., 2006
Polymer composite	17-54	Zahn et al., 2001
Pegulit	91	Horning et al., 1999
Wood chips	17-91	Guarino et al., 2006
Corn stalks	37-60	Guarino et al., 2006
Zeolite on permeable cover	90	Miner & Pan, 1995
Polystyrene foam	45-95	Miner and Suh, 1997

5. LAND APPLICATION STRATEGIES

Significant ammonia volatilization can occur when manure is surface-spread to fertilize crop and pasture fields. Minimizing time of manure exposure on the ground surface is the most effective strategy for reducing ammonia emissions during or after field application of manure. Direct injection, prompt plowing-in, increased infiltration, and washing-in after applications are some of the methods available to limit this exposure time. Combining these improved field application techniques with other ammonia holding techniques, such as use of additives, improves the ammonia utilization efficiency of crops and pastures, which further decreases ammonia volatilization. A summary of the efficacy of various application strategies in reducing ammonia emissions is given in Table 6.

In practice, direct injection or immediate incorporation of manure into the soil reduces ammonia losses better than other application methods. Direct injections to within 3-30 cm-depths reduced ammonia volatilization by 47 to 98% compared to surface applications (Hoff et al., 1981; Thompson et al., 1987; van der Molen et al., 1990; Svensson, 1994; Rubaek et al., 1996; Morken and Sakshaug, 1998; Smith et al., 2000; Sommer and Hutchings, 2001). Where direct injection or immediate incorporation has not been an option, other surface placement methods such as band spreading, trailing shoe, and shallow slot injection have been more effective than surface broadcasting. These practices have been reported to reduce ammonia losses by between 39 and 83% compared with surface broadcasting (Thompson et al., 1990a; Svensson, 1994; Frost, 1994; Smith et al., 2000). Some of these researchers (Thompson et al., 1990a; Svensson, 1994), however, have pointed out that, with time, band spreading is not much more effective than surface broadcasting.

Research has also shown ammonia losses from surface applied slurry are inversely related to infiltration. One method of increasing manure infiltration into the soil is manure dilution with water. Manure slurry diluted with water has been observed to reduce ammonia losses by 44 to 91% (Sommer and Olesen, 1991; Stevens et al., 1992; Frost, 1994; Morken and Sakshaug, 1998). Another method of increasing infiltration is cultivating the soil surface or increasing the surface roughness. Cultivating the soil surface before surface application of slurry reduced ammonia losses by between 40 and 90% compared to uncultivated soils (Sommer and Thomsen, 1993). A similar method of increasing infiltration is cultivating the top 6 cm of the soil to mix applied slurry with soil. This manure-soil mixing reduces ammonia loss by as much as 60% compared to surface application (Van der Molen et al., 1990). Other research has shown infiltration is also higher at low soil moisture contents, and slurry application at lower soil moisture reduces ammonia loss by as much as 70% (Sommer and Jacobsen, 1999). The inverse relationship between ammonia loss and the rate (volume/area/time) of slurry application suggests intermittent slurry application might also reduce ammonia loss because of improved infiltration (Thompson et al., 1990b).

Ammonia losses from manure applied during crop growth periods may be reduced by using trail hoses, which apply the slurry onto the soil between rows of plants (Bless et al. 1991; Holtan-Hartwig and Bockman, 1994) or by using a trailing shoe (Smith et al., 2000). The reduced ammonia loss is attributed to immediate absorption of NH_3 by plant leaves and roots, reduced slurry exposed surface, and canopy modified microclimate not favorable for ammonia volatilization (Holtan-Hartwig and Bockman, 1994; Thompson et al., 1990).

Atmospheric conditions play an important role in ammonia loss reduction during slurry application. Sommer et al. (1991) reported a linear increase in ammonia volatilization between 0 and 19°C during a 24 h period. In the same study, ammonia loss increased significantly when wind speed increased to 2.5 m/s, but no consistent increase in ammonia loss was recorded between 2.5 and 4.0 m/s wind speeds. In an earlier study, increasing wind speed from 0.5 to 3.0 m/s increased ammonia loss by about 29% in 5 days (Thompson et al., 1990b). These observations suggest manure applications should be scheduled during non-windy periods.

In practice, direct manure injection or manure incorporation into the soil adds to the costs of manure application. However, the cost of injection or manure incorporation into the soil during land application to reduce ammonia emissions may be recaptured in terms of better crop yields due to a more efficient utilization of the applied manure. Considering other environmental benefits accruing from reduced ammonia loss, as well as costs that may be incurred in legal conflicts due to ammonia emissions, these practices can be economically justified.

Table 6 - Summary of livestock manure application strategies for abatement of ammonia emissions

Application Strategy	Emissions reduction (%)	References
Direct injection	47-100	Hoff et al., 1981; Thompson et al. 1987; Rubaek et al., 1996; Morken & Sakshaug, 1998; Smith et al., 2000; **Thompson & Meisinger, 2002;** Svensson, 1994; Van der Molen et al, 1990; Huijsmans et al., 2003; Hansen et al., 2003.
Slot injection	80-92	Morken & Sakshaug, 1998; Frost, 1994; Huijsmans et al., 2001
Band application	0-65	Thompson et al., 1990a; Smith et al., 2000; Morken & Sakshaug, 1998; Huijsmans et al., 2001
Trailing shoe	43	Smith et al., 2000
Slurry dilution	44-91	Morken & Sakshaug, 1998; Frost, 1994; Sommer & Olesen, 1991;
Low soil water content	70	Sommer & Jacobsen, 1999
Soil surface cultivation	40-90	Sommer & Thomsen, 1993; Van der Molen et al, 1990; Huijsmans et al., 2003; Rochette et al., 2001.

SUMMARY AND CONCLUSIONS

Reducing N excretion through dietary changes can effectively mitigate ammonia emissions from livestock operations. In ruminants, reducing the CP intake by as little as 5% can reduce ammonia emissions by as much as 74% from excreted manure. For non-ruminants, similar ammonia emission reductions have been observed by replacing CP with amino acids.

All of the urine-feces segregation methods evaluated and reviewed have reduced ammonia emissions from livestock barns by about 50% compared to the conventional manure handling systems. Therefore, the critical factors that need to be considered in making the choice of method for separating urine from feces from these method are the cost of installing the system, maintenance, and ease versus cost of operation. The closely related use of urease-inhibitors for control of ammonia emissions in CAFO has been somewhat successful at the laboratory level, but there is no pilot or full-scale application reported in the literature. The lack of information of its efficacy at pilot or full-scale facilities may partly explain why urease-inhibitors have not been employed for on-farm control of ammonia emissions. This lack of adoption may also be attributed to the unknown effects of these chemicals on the crops or pastures where the treated manures are ultimately utilized.

Acids and acidifying salts are effective at holding ammonia in ammonium form. However, strong acids reduce slurry pH more cost-effectively than the weaker acids and acidifying salts. In addition, because strong acids are more hazardous for use on the farm that acidifying salts and weaker acids, the latter although less effective than the strong acids, they are more suitable use on-farm. Among ammonia binding amendments, zeolite and sphagnum are more effective for reduction of ammonia loss in manure slurries or liquid than in solid poultry manures. Yucca extract (saponins) does not seem to as effective as either zeolite or peat moss in mitigating ammonia emissions.

There are a number of other amendments with various brand names, but their mode of operations is not known. It is important for producers to ensure that the effectiveness of these additives have been scientifically verified by independent and reputable institutions before they can adopt them for use in their facilities. Often, large amounts of the product are required and in most

cases such as the use of acid/acidic salts, precautions must be taken to safeguard the safety of livestock and farm workers. In addition use of acids may result not only in an undesirable increase in the mineral content of the manure/litter, but also in the corrosion of equipment and structures. Selection of appropriate application methods for effective use of these additives is very important. Currently, there is a lack of standardized application and evaluation protocols for these additives.
Impermeable covers are more effective than permeable covers in ammonia mitigation strategies from manure storages. However, if no biofilters are used to clean up the trapped gases under impermeable covers, excessive ammonia and other gaseous emissions may occur during land application. Although the biggest hurdle in the installation of impermeable lagoon covers on swine farms is the initial purchase price of the cover, another major consideration is availability of more land base required to receive the conserved N.

Biofilters exhibit a wide range of performances (9 to 100% effectiveness) in the removal of ammonia in carrier-air. This variability in effectivness may be attributed not only to the wide range of biofilter-materials, but also on other factors such as maintenance of optimum moisture in the filter bed, the residence time of the air in the biofilter, the ammonia load in the incoming air, and how well the microbial community is established in the biofilter. However, these systems can effectively be used to mitigate ammonia emissions from livestock operations. There is also a wide variation in the effectiveness of other ammonia filters (scrubbers and trickling filters). Process control with pH and automatic water discharge were sufficient to guarantee ammonia removal efficiency in acid scrubbers, while process control is required in biotrickling filters to guarantee ammonia removal efficiency.

Although more costly, direct manure injection or manure incorporation into the soil are the most effective (up to 98%) methods for mitigating ammonia emissions amongst methods of manure application to soil. However, the extra costs of injection or incorporating manure into the soil may be recaptured in terms of better crop yields because of more efficient utilization of the applied manure. Direct injection, or immediate incorporation into the soil become not only attractive practices, but also may be economically viable considering other environmental benefits accruing from reduced ammonia volatilization, as well as cost that may be incurred in legal tussles due to the ammonia releases.

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STANDARDIZED TESTING AND REPORTING FOR MITIGATION TECHNOLOGIES

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Keywords. Mitigation, Protocol, Standardization, Emissions.

INTRODUCTION

Airborne emissions of gases and particulate matter from livestock production facilities are a critical issue facing the livestock industry from both an environmental and regulatory perspective. Additionally, odor emissions are a concern for both the farmers and nearby neighbors. An array of projects have and are attempting to quantify air emissions from buildings, open lots, and manure storage systems through both short- and long-term monitoring using a variety of equipment and measurement protocols. Recent projects funded through producer organizations, the CSREES-NRI and the USEPA have resulted in a lengthy set of Standard Operating Protocols (SOPs) that must be followed to quantify actual ammonia and hydrogen sulfide emissions. Although quantifying actual emissions is essential, there is also a critical need to quickly, accurately, and inexpensively quantify the effectiveness of emission mitigation technologies. Although a less expensive and quicker means of quantifying emissions or emissions reductions may be slightly less accurate (absolute), a reasonable trade off seems very beneficial to all of the parties involved.

Currently, systems for reducing emissions of air pollutants are being developed by research universities/institutes and private industry. However, the lack of standard protocols for quantifying and documenting the effectiveness of these mitigation systems is slowing the adoption and development of these technologies. In addition, the lack of standard quantification and reporting methods for air emission mitigation technologies makes it difficult for the regulatory community (local, state and federal) to confidently assign Best Management Practice (BMP) status to these technologies and for the agricultural community to confidently invest in these technologies. This lack of quantitative information on mitigation technology effectiveness is limiting the development and implementation of these technologies in Minnesota and other states and thus hindering the development of the animal agriculture industry in the USA.

This paper presents a draft mitigation technology testing protocol developed in Minnesota and funded by the Minnesota State Legislature through the Minnesota Department of Agriculture (2007). It is intended that this draft be used as a starting point for discussing the critical issues in development of a national standard for mitigation technology testing. Note that this protocol is focused on quantifying emission reductions for a mitigation technology (compared to a control) rather than assessing the absolute flux rate from an emission source. Reported results using this protocol will be in terms of percent reductions expected along with some measure of statistical confidence for these reported reductions.

Three key components are involved in this testing protocol and described in more detail below. Initially some assessment of the technology should be made to determine the scientific merit of the technology and the likelihood that further testing has some potential to show reasonable results. Secondly, a experimental design specific for the technology must be developed. Finally, a summary of the test data should be reported in a standard way that allows for comparisons between different mitigation methods. A preliminary discussion of all of these steps is provided in the Minnesota Draft Protocol as reported below.

MINNESOTA DRAFT PROTOCOL (SUMMARY)

INITIAL SCREENING

To increase the likelihood of a successful evaluation, it is important that some baseline parameters are met prior to testing. This initial screening includes a description of the technology along with some estimates of emission reductions to be expected and a description of the farms or production units that will be used as test sites.

Technology Description

Descriptions of the treatment technology and treatment principles are required prior to any testing. Trade secrets do not need to be revealed but some general description related to the general principles governing the technology need to be stated. This section should also include factors that may affect treatment performance (e.g. ventilation rate, moisture content, feedstock).

Preliminary Reduction Estimates

Estimated or claimed reductions for all gas emission reduction claims (e.g. hydrogen sulfide, ammonia, odor, VOC's) must be included in the report to help guide the validation protocol. Claims must be substantiated by a preliminary investigation showing a minimum of 20% reduction, literature citations of similar technologies, or overwhelming anecdotal evidence. Reductions of less than 20% are difficult to validate because of the variability of the systems and measurement methods and maybe not worth the producers efforts to implement. The use of gas detection or diffusion tubes, or other similar inexpensive methods, are acceptable for these preliminary reduction estimates.

Test Sites

Provide detailed information on two or more farms where the technology is currently in place and where testing will likely be conducted. Note that the technology must be in operation six months prior to testing unless justification is made for shorter or longer acclimation times. For instance, justification for testing a microbial treatment technology may be that evidence shows that microbial environmental parameters typically stabilize (moisture, pH, DO, etc.) within a shorter period of time. In any case, it is important that all waste manure?? streams being treated have stabilized and masking smells from air treatment technologies have been normalized (e.g. specific smells from wood chips) prior to testing This time period would vary depending on the treatment technology.

Include information that is critical to the technology performance such as: type of source (manure storage, building, etc.), size of building or volume and size of manure storage basin, size of building or volume and size of manure storage basin, amount of manure treatment per day (loading rate of manure and dosing frequency), ventilation rate of building or fan performance information, description of any pretreatment technologies in place that are critical to the performance of the technology (e.g. solid liquid separation), addition of other organic material to the system (e.g. byproducts or other waste), and the potential impact of those additions on the technology performance.

EXPERIMENTAL DESIGN GUIDANCE

Testing protocols must be based on sound statistical methods for the determination of the number of installations tested, the number of samples taken and the type of measurements taken. General protocols are outlined below but specific sampling and protocols may be technology specific and should be addressed and accepted by the Research University or third party responsible for the testing. In general, however the following conditions must be met.

1. The technology must be in place and acclimated appropriately.
2. Measurements must be made at the range of standard operating conditions for the technology – which likely will include seasonal differences.
3. After each set of measurements, the data should be evaluated to determine if the testing protocol is correct and if the technology provider wishes to continue the evaluation. (For instance, if technology is not showing any reduction the funding supplier (company or granting agencies) of the testing may decide to discontinue the testing.)
4. Protocols must be developed specifically for each technology evaluation. Sections below provide some guidance on protocols for evaluating manure treatment technologies (e.g. additives, anaerobic digestion) or air treatment technologies (e.g. biofilters, wet scrubbers).

In all of the protocols, it is critical to note the type of analyzer used for quantification and adhere to the calibration and operating protocols for the equipment. This may include calibration schedule, operating temperatures, and maintenance items. The following is a list of acceptable equipment that can be used in the testing protocol.

Table 1. Proposed acceptable equipment for monitoring (Minnesota Draft).

Equipment Type	*Gas measured*	*Measurement Error (SD)*
Hydrogen Sulfide Analyzer, Model 45C, Thermal Environmental Instruments, Franklin, MA	H_2S	
Hydrogen Sulfide Single Point Monitor, Zellweger Analytical Lincolnshire, IL	H_2S	
Jerome Meter Model, Arizona Instruments, Phoenix, AZ	*Reduced Sulfur*	
Ammonia Analyzer, Model 17C, Thermal Environmental Instruments, Franklin, MA	NH_3, *NOx*	
Anova Ammonia Analyzer	NH_3	
Gas Detector Tubes, Gastec Corporation.	NH_3, H_2S	
Tapered Element Oscillating Microbalance (TEOM), Model 1400a, Rupprecht and Patashnick, Albany, NY.	PM_{10}, $PM_{2.5}$	
MiniVol portable air sampler, Airmetrics, Eugene, OR	PM_{10}	
[1]*ACCENT® International Olfactometer, St. Croix Sensory, Inc. Stillwater, MN*	*Odor*	
GS/MS	*VOC*	
Open Path FTIR	*VOC*	

[1]*Odor collection and evaluation done according to CEN 13725.*

Manure Treatment Experimental Design Protocols

Treatment technologies such as additives, anaerobic digestion and aeration have been used to reduce odor and gas emissions from buildings, manure storages, and land application. Quantification of emission reductions from manure is challenging for a variety of reasons that must be addressed in the validation protocol. For example, the following issues may have an impact on measurements and should be addressed in the experimental design.

1. Crusting of the manure surface can interfere with measurement and often may be a more dominant factor in reducing emissions than the specified technology. For instance, anaerobic digestion may result in less odorous emissions but if there is no solid separation after digestion a crust will likely form on the manure storage structure. This crust will limit emissions from this structure despite the effectiveness of the anaerobic treatment.
2. Finding a site to use as a "control" for comparing treatment effectiveness is challenging. Management, diet, genetics, and other factors often result in different emissions from similarly designed manure handling systems.
3. Diurnal and seasonal variation in temperatures, humidity, wind, etc. will result in microbial changes in the manure which in turn impact emissions. This must be considered in the protocol by repeated measurements in different seasons.
4. Manure treatment such as pit additives may be shown to reduce emissions from a manure storage but that same reduction may not apply in evaluating emission reductions for an entire deep pitted facility because emissions are also likely from the flooring, animal, feeders, etc.. This fact must be made clear in the technology claims and in the testing protocol.

Micro-meteorological methods, flux chambers, wind tunnels, and a new method using a micro-tunnel could be used for validating reductions from manure treatment technologies. These methodologies must clearly be defined in the protocol.

Laboratory quantification (laboratory simulation of manure treatment in small vessels) may provide a controlled environment for documenting emission reductions; however, laboratory conditions likely do not reflect field conditions. As such, reductions determined using laboratory methods may not be acceptable.

Manure chemistry, predicting emissions based on concentrations of specific chemicals in manure and the physical and chemical processes governing emissions, has not been validated (mass transfer models are adequate for dilute aqueous solutions but may not be valid for concentrated wastewater such as manure storage basins). As such, such methods cannot be used for reduction quantification or verification of manure treatment.

Air Treatment Experimental Design Protocols

Biofiltration and wet-scrubbers are examples of two air treatment technologies. For these types of technologies sampling methods are a critical factor in the technology assessment. to As such, any sampling protocol must include provisions for sampling the entire exhaust air stream <u>or</u> the fraction of air that has been sampled should be documented. For instance, biofiltration on pit fans can be tested by evaluating samples pre- and post- biofilter. However, this same emission reduction can only be applied to the entire building if the entire exhaust air stream goes through the biofilter. Similarly, a technology that captures only a fraction of air being exhausted (some air bypassing the filter) must be tested with a protocol that quantifies this bypass air. Note that quantification of absolute ventilation rates is not necessary for air treatment technology validation when sampling occurs pre- and post-treatment and the samples are taken at the same ventilation rate (and same time). Some estimate of ventilation rate during the sampling time, based on fan performance curves should be included in the report as it is likely the treatment effectiveness will be somewhat dependent on flow rate.

Two methods are acceptable for evaluating emission reductions.

1. Exhaust air can be measured semi-continuously or continuously for a minimum of 24 hours per sampling event. The semi-continuous measurements must switch from pre-treatment and post-treatment samples at intervals less than 30 minutes. If the technology claims to treat air at various flow rates, the protocol must include measurements at the minimum and maximum flow rates. Real-time gas analyzers are needed if conducting continuous monitoring. The experimental design must include a minimum number of samples at different times of the year (assuming that the technology's performance may vary seasonally). It is assumed that, at a minimum, testing will be done in three different seasons.
2. Comparing pre- and post-treatment grab samples are also a valid means of a technology evaluation. Grab samples can often be collected pre- and post- treatment simultaneously resulting in data that may be very reflective of actual performance. As with continuous measurement, samples should be taken in the typical range of ventilation rates to quantify reductions at these different flow rates. Grab samples can be collected in Tedlar bags or similar but should be evaluated within a time frame appropriate to the chemical being evaluated. Sample collection in Tedlar bags are not recommended for VOC quantification. Instantaneous analyzers that generate a snapshot for the concentration of gas or dust is typically used in these cases although analyzers that use a time-weighted average method such as a gravimetric device for measuring PM can still be used over relatively short periods of time.

Dust sampling (PM_{10}, $PM_{2.5}$, Total Dust, Respirable Dust, etc.) of exhaust air is challenging. Most of the equipment is not designed for sampling in exhaust streams with high air velocities. As such, care must be taken to insure the flow rates across these samplers are appropriate.

Technologies installed on naturally ventilated barns will not be accepted protocols due to the difficulty in obtaining representative samples pre- and post- treatment.

Statistical Evaluation
A Student t-test run at the 90% confidence interval is required for determining % reductions. For systems where there testing is done on independent samples (vs paired samples), an independent t-test should be used. For example, testing of a manure additive cannot be a "pre-" and "post-" type of test. In this situation, emissions from the barn with the additive would be compared to other similar barns where no additive is used. In this case either a set of "control" barns could be evaluated for mean and standard deviation and compared to the treated barns mean and standard deviation using an independent t-test.

The t-test for this independent sampling uses the following equations.

Test parameters: μ_1 *= average emission value for control sites*
μ_2 *= average emission value for treated sites*
$\mu_1 - \mu_2$ *= the difference in average emissions*

To determine the probability of a specific reduction in emissions the following would be the null hypothesis.

$$H_0 \Rightarrow (\mu_1 \cdot (1 - \frac{\%red}{100})) \leq \mu_2$$

The test statistic is

$$z = \frac{x_1\left(1 - \frac{\%red}{100}\right) - x_2}{\sqrt{\frac{s_1^{\,2}}{n_1} + \frac{s_2^{\,2}}{n_2}}}$$

Where

z = probability
red=the anticipated emission reduction
x = mean of data set
s = sample standard deviation
n = number of samples

Using level of significance of 0.1, the upper tailed critical value is 1.28. The null hypothesis would be rejected if z<1.28. (To be 90% confident that the anticipated reduction has been achieved the value of z must be greater than 1.28.)

Example: 10 samples were taken from several similar dairy manure storages. The samples had a mean hydrogen sulfide emissions of 69 (SD=50). Six samples were taken from a manure storage that was treated. The mean of these samples was 30 (SD=25). If we would like to claim a 20% reduction with 90% confidence interval the following calculation would be made.

$$z = \frac{69 \times \left(1 - \frac{20\%}{100}\right) - 30}{\sqrt{\frac{50^2}{10} + \frac{25^2}{6}}}$$

$$z = 1.33$$

Because z is greater than 1.28 we can be confident that there is a 20% reduction with this technology. Note that the mean reduction for this example is 57% (1-30/69) but due to sample size and variability, the paired t-test is showing that only a 20% reduction can actually be achieved.

Reporting Requirements

Reporting requirements for the testing must include the following information.

1) A brief technology description and summary of testing protocols and results. Also included in this section must be a listing and description of the farm sites used in the testing. Photographs may be included to help visualize the technology.
2) A summary of the experimental must be submitted with the final testing report. This section must include specific information regarding the actual data taken such as the number and dates of all site visits, the number of samples taken at each visit. In addition,
3) Finally, for each sampling event all critical site specific data such as ambient temperatures or specific management issues during the time of sampling must be noted. All of the raw site data must be reported in table format. A statistical analysis of the data and summary must be presented with any deviations from the original experimental design protocol explained.

1) Preliminary Information
Company, Technology Name, Primary Contact, Address, Phone/fax/email, Testing Application Date

Item	*Description*
Technology Description	
Reduction Estimate and Basis for Estimate *:*	
Test Site 1*: Farm name, primary contact, address, phone, email, summary of operation, specific information on source where technology is installed.*	
Test Site 2*: Farm name, primary contact, address, phone, email, summary of operation, specific information on source where technology is installed.*	
Test Site 3*: Farm name, primary contact, address, phone, email, summary of operation, specific information on source where technology is installed.*	

2) Written Protocol

Item	***Description***
Type of Testing (Manure or Air)	
Number and names of of sites being tested. *(e.g. samples will be collected at the Johnson, Smith and Wilson site as listed in preliminary assessment forms)*	
Number and timing of site visits *(e.g Samples collected in May-June, July-August, Sept-October at each of three sites.*	
Number of samples taken per site visit. *(e.g. 24 hour sampling or grab samples)*	
Sample collection method and description *(e.g. continuous measurement equipment on site. switching sampling lines from control to treatment every 30 minutes over a 24 hour sampling period. Ventilation rate held constant throughout sampling period.)*	
Type of Measurements Made and Specific Equipment Used *(use reference numbers from Table 1)*	
Description of baseline or "control" measurement including sampling location and sample collection method. Include farm names. *(e.g. Johnson farm, east pit fans, sampling line inserted on suction side of fan)*	
Description of "Treatment" Measurement including location and sample collection method. Include farm names. *(e.g. Johnson farm, east pit fans. Samples taken in exhaust stream of shroud constructed to capture all exhaust gases from treatment system.)*	

General Information for Sampling Events for Farm #1 (add additional tables for additional farm sites tested)

General Information	*Sampling Event 1*	*Sampling Event 2*	*Sampling Event 3*
Date and time of sample collection			
Current status of source – number of animals, weight of animals, etc.			
Notation of any system changes, breakdowns or modifications within previous 30 day period.			
Most recent operation or maintenance of the system noted (e.g. filter replacement)			
Ambient temperature at sampling			
Exhaust temperature at sampling (if air sampling)			
Other meteorological conditions that might impact sampling results.			
Samples Taken and IDs			

Data Reporting Form

Farm ID	***Date***	***Time***	***Pre or Post***	***Grab or Cont.***	***H_2S (ppb)***	***NH_3 (ppm)***	***Odor (DT)***	***PM10 (µg/m3)***

Note that this form can be modified for the specific technology and sampling protocol.

STATISTICAL ANALYSIS

A complete statistical analysis as outlined in the original protocol (t-test or other). Additional statistical analysis and summary should also be included if deemed necessary. If possible, photos should be included to show the testing methodology.

SUMMARY

This paper was written as a means of initiating a discussion regarding the need to develop quick and inexpensive standardized procedures for evaluating air emissions from livestock and poultry facilities. A draft protocol of such a method was presented as a means of communicating the types of information that might be included in such a standard protocol. Note that the emphasis for this protocol is NOT to determine absolute emissions but rather determine, with some degree of confidence, anticipated reductions in these emissions that would result from the implementation of mitigation technologies that have been tested using a standard set of procedures.

There are a variety of items that could be included in such a protocol development. Most importantly, it is critical for such a protocol to have widespread adoption by both the industry and the regulatory community. This would likely come about through a large national project with advisors representing all interested parties. However, once developed, such a protocol would vastly improve the development and implementation of new mitigation technologies. Currently the development of such standard protocols is occurring in the Netherlands (Mosquera and Ogink, 2006) related to ammonia emissions and for odor measurements in Germany (Both, personal communication, 2008).

Acknowledgements

Development of the Minnesota Draft Protocol was made possible through a grant from the Minnesota State Legislature through the Minnesota Department of Agriculture.

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STANDARDIZED TESTING PROCEDURES FOR ASSESSING AMMONIA AND ODOR EMISSIONS FROM ANIMAL HOUSING SYSTEMS IN THE NETHERLANDS

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Abstract. *The Green Label measurement protocol (GL protocol) was developed in the mid nineties to evaluate the ammonia emission of low emission housing systems and other mitigation measures in the Netherlands. The measurements are used to assign official emission factors to low emission housing systems, used in farm permit procedures. More recently a new multi-site sampling approach has been developed, based on the experiences with the GL protocol and results from a statistical analysis of an extensive ammonia emission database. The objective of this paper is to describe and explain the evolution process from the GL protocol to the multi-site approach. Key features of the GL protocol are: evaluation at one farm location, long measurements during winter and summer periods, continuous high frequency sampling, ranges to stay within for critical management factors. In 2005 a statistical analysis was performed on a large ammonia emission database of pig housing systems that provided estimates of so called between farm(σ^2_b), within farm (σ^2_w) and instrumental measurement variances that determine the accuracy with which the mean ammonia emission of a housing system can be measured. The analysis demonstrated that both σ^2_b and σ^2_w of housing systems varied in the range of 30 - 40% (relative standard deviations). The large size of σ^2_b implies that the accuracy of the GL protocol is strongly limited by its single farm approach. Recently a new multi-site sampling approach has been approved based on four farm locations where at each location six independent 24h sampling intervals are distributed over one year. The multi-site approach allows for a less intensive and less costly measuring effort for each location, whereas the accuracy of the mean yearly ammonia emission of a low emission housing system is drastically improved.*

Keywords . *ammonia, odor, emission, animal housing, measurement method.*

INTRODUCTION

In many parts of the world large scale livestock operations are increasingly concentrated in regions with favorable production conditions and close access to consumer markets. In Europe main swine and poultry producing areas can be found in the north (e.g. Denmark, Niedersachsen in Germany, the Netherlands, Brittany in France,) and the south (Lombardy in Italy, Catalonia and Galicia in Spain). Expansion and specialization have enabled higher productivity level at the farms and, without doubt, improved farmers' income and living standards in recent decades. However there are drawbacks that are related to animal welfare and health issues and, especially where animal production has been concentrated in restricted areas, environmental pollution. Main environmental concerns are related to the emissions of ammonia, odor and more recently PM10 and greenhouse gases. In the Netherlands this intensification process started in the sixties, initiating the development of a regulatory framework to control odor nuisance and to protect natural ecosystems. From 1990 on it became clear that large scale implementation of emission mitigation techniques on farm level was required to meet national and EU ammonia emission ceilings. A number of measures were imposed including mandatory manure application techniques and cover of all liquid manure storages. At the same time the implementation of new housing systems with low ammonia emission was stimulated under the so called Green Label framework, an agreement between agricultural industry and government. In this approach an evaluation scheme was required to assign ammonia emission factors to housing systems. For this purpose a measurement and evaluation protocol (Groen Label, 1996) was developed (referred to as GL protocol) that had to be applied before housing systems were allowed on the Green Label list with approved low emission housing systems and other mitigation measures. Although Green Label has been incorporated since 2000 in the national regulatory framework to control ammonia emission from livestock production (Infomil, 2008), the GL protocol still has been in use for assessing low emission housing systems and mitigation measures like air scrubbers. Similar to the GL protocol using the same setup, an odor measurement protocol was developed for assigning odor emission factors to livestock housing systems (Ogink & Klarenbeek, 1997). More recently new approaches have been developed, based on the experiences with the GL protocol and statistical analysis of extensive ammonia emission databases (Mosquera & Ogink, 2005), that will lead to the replacement of the GL protocol in 2008 (Ogink et al., 2008). The new approach introduces a strongly modified measurement strategy. New protocols, using the same modified measurement strategy based on multi-site sampling, are defined for the emissions of ammonia, odor, PM10/PM2.5, methane and nitrous oxide.

The objective of this paper is to describe and explain the evolution process from the GL protocol to the multi-site approach. First the main characteristics of the GL protocol will be shortly summarized. The lessons learnt from the GL approach, including its main shortcomings will be outlined in the second part. In the third section the modified measurement strategy will be introduced and discussed. The main conclusions and implications will be summarized at the end of this section.

GREEN LABEL PROTOCOL FOR THE MEASUREMENT OF AMMONIA EMISSION

The Green Label protocol was developed to evaluate mainly new housing systems equipped with modified pen designs and manure removal techniques to lower ammonia emission. All main animal categories took part, each with their own specific housing systems. In a later phase, evaluation of different types of air scrubbers connected to animal housings also were included. The main goal of the evaluation was to estimate accurately the mean annual ammonia emission from the investigated system, expressed per available animal place (kg NH_3 $year^{-1}$ animal $place^{-1}$). The protocol was developed and described by an independent technical working group that evaluated all measurements carried out according to this protocol and that advised on the certification of Green Label housing systems (Groen Label, 1996). The main elements are:

- Housing systems can only be evaluated under real farm conditions. The majority of measurements have been carried out at commercial farms. In some cases experimental stations were used that applied standard management. The protocol defines the minimum number of animals during evaluation.
- The evaluation focuses at sampling and measuring at a single farm location. To ensure that this single location is representative during the measurement, ranges for all critical management factors that may affect ammonia emission are defined in the protocol. These ranges should represent standard management for feeding, hygiene and ventilation, and are monitored during the measurement period. Furthermore minimum technical performance levels are defined to ensure representativeness.
- The measurement strategy defines two sampling periods that represent the cold and the warm season. For each animal category the sampling period is specified in the protocol. In general for animal categories without growth cycles (laying hens, sows, dairy cattle) minimum sampling periods are 4 weeks in summer and 4 weeks in winter. For categories with growth cycles (fattening pigs, broilers) full cycles during both summer and winter time have to be measured.
- The ammonia emission has to be monitored on an intensive 'continuous' basis, i.e. every 5-10 minutes a measuring cycle has to be performed. Rules are specified for data handling and calculations. Concentration and ventilation rates have to be aggregated to 1 hour average values. The average daily emission is calculated from the 1 hour averages, only if enough hourly averages are present, otherwise missing values are recorded. The overall mean emission is calculated from the 24 hour means.
- Methods and equipment to be used for concentration and ventilation rate measurements are described in a special technical guide (van Ouwerkerk et al., 1993) that lists all allowed approaches. For ammonia concentration the NO_x-monitor using the chemoluminesence principle is the preferred method because of its low detection threshold. Ventilation rate is determined by making use of fan wheel anemometers in ventilations shafts that are before and after measurement periods calibrated in wind tunnels. The methods from the technical guide are mandatory unless the Green Label working group allows other methods because of technical restrictions. For example in case of air scrubbers use is made of the impinger method instead of the NO_x-monitor because of the extreme humidity in the outlet air.
- All evaluations have to be reported according to guidelines that include a clear description of the evaluated mitigation system, used measurement methods and farm conditions as outlined before, results, and discussion of the results and functioning of the system.

The vast majority of measurements were carried out by a specialized team within the former institute for agricultural and environmental engineering (IMAG), but in smaller numbers also by groups within the applied research centers for pigs and poultry. All these groups are integrated now in the Animal Sciences Group of Wageningen University and Research Centre. In total about 80-90 system evaluations, based on the GL protocol, have been published in public technical reports. Initially measurements were fully or to a large extent financed by government funds to stimulate the development and implementation of low emitting housing systems. In a later phase the funding role of industry became increasingly important.

The GL protocol served as a basis for an odor measurement protocol that was used in the odor research programs from 1997 on for quantifying odor emissions from housings of the main animal categories. The same framework was used with the difference that continuous sampling of ammonia was replaced by 5 times sampling in summer and 5 times in winter time during a 2-hours period between 10 and 12 a.m. Odor samples were analyzed according the NVN2820 olfactometry standard that was replaced in 2004 by the European standard EN13725. Details of this odor measurement protocol are described by Ogink and Groot Koerkamp (2001).

LEARNING BY DOING: LESSONS FROM THE GREEN LABEL PROTOCOL

The GL protocol facilitated a standardized process of routine evaluation of a wide variety of housing systems in all main animal categories. It is at the basis of the regulatory list that specifies all available housing systems and their assigned ammonia emission factors in the Netherlands. This list and the system descriptions can be accessed at the website of the Infomil agency (Infomil,

2008) and is yearly updated with new systems. The ammonia factors are used in license procedures for modification and new construction of livestock facilities and are one of the critical factors that in many cases determine the scale of operation. Given their impact on livestock industry and environmental protection their reliability and accuracy are considered important by all involved parties.

From the nineties on the GL measurements contributed significantly to the knowledge of underlying processes related to the emission of ammonia and other gaseous compounds. Gradually a strong basis of on farm measurement experience was built up, that involved not only an efficient organization of measurements, but also extensive knowledge of the role of a wide variety of farm management factors that is of high importance for a proper interpretation of the recorded data. However, as more and more datasets became available, it became clear that emission factors possibly were not that accurate as suggested by the decimals used in the regulatory list. Measurement on housing systems with minor design differences, showed much larger deviations than expected from the system differences alone. Another aspect that drew increased attention and caused concern was the cost level of the GL protocol.

An insight in the mechanisms that determine the accuracy of protocols for emission factors was presented as early as 1997 in a study by Ogink and Klarenbeek (1997). Although this study dealt with the accuracy of odor measurements carried out with a measurement strategy based on the GL protocol, the principles of the presented statistical variance component model could be used as well for other emission components. However to make use of this approach reliable estimates were required of different variance components that can only be derived from a large quantity of measurements sets that were not available at that time. In 2005, having sufficient available ammonia emission datasets, Mosquera and Ogink (2005) carried out a statistical analysis with the same variance component model to estimate the required variance components for assessing the accuracy of the GL protocol. The model is based on distinguishing between three variance layers in the sampling design:

- Between-farm variance (σ^2_b): variance resulting from factors and variables that cause systematic differences between farm locations within the same housing system. Such factors can be related to different management practices between farms, like different feeding- and ventilation regimes, different hygiene standards, but also small differences in pen layout within the same system.

- Within-farm variance(σ^2_w): variance resulting from factors and variables that cause day to day fluctuations in emissions of a specific farm location. Such factors can be related to seasonal factors that affect ventilation levels and correlated emission levels throughout the year, but also production factors like present animal numbers and mass, feed intake and manure excretion.

- Instrument measurement variance (σ^2_m) : variance resulting from random measurement error of instruments used in emission measurements. Both instruments used for measuring concentrations and instruments used for determining air flows are subject to this type of error.

Each variance component attributes to the overall measurement variance of the mean emission of a housing system (σ^2_{total}) as described in the model equation below:

$$\sigma^2_{total} = \frac{\sigma^2_b}{k} + \frac{\sigma^2_w}{k \cdot l} + \frac{\sigma^2_m}{k \cdot l \cdot m}$$

The equation reflects σ^2_{total} in a sampling design with k farm locations, l measurement events within each location and m measurements within each measurement event on a location. The model shows that the between farm component σ^2_b plays a key role in the magnitude of the overall measurement variance, because it can only be downscaled by k. Factor k, representing the number of locations, plays a key role as it affects the contribution of all variance components In the GL protocol k=1, i.e. measurements are carried out on a single location, meaning that σ^2_{total} can never be smaller than σ^2_b. For ammonia emission Mosquera & Ogink (2005) demonstrated that both σ^2_b and σ^2_w of housing systems varied in the range of 30 - 40%, when expressed as relative standard deviations. These values were found in statistical analyses carried out for the pig category: fatteners, sows, farrowing sows, piglets. Our impression is that the same order of magnitude is to be expected for housing systems in poultry and cattle. Similar findings for large between farm variation in odor emission were found by Ogink & Klarenbeek (1997) and later in a more extended analysis by Mol & Ogink (2002). From these findings the following conclusions and implications can be formulated:

- The GL protocol neglects sampling in the variance layer that represents important systematic differences between farms as a result of different management practices. Despite having ranges defined in the protocol for critical management factors, variation between farms remains very large, much larger than ever anticipated before. Increasing the number of farm locations in the sampling design is the only way to downscale this type of variance and thus to improve overall accuracy.

- For the purpose of estimating the mean annual emission of a housing system, high measurement frequencies during sampling periods that may take several weeks up to two times four months (in case of fattener cycles) do not contribute to the overall accuracy at all. Given the size of σ^2_b and the dominating role of k in the component model, it can be easily calculated that for example decreasing replication number l from 60 to 6 does not increase overall accuracy. Here cost reductions can be implemented by applying less frequent sampling schemes without affecting accuracy. However, for the purpose of gaining insight in the emission process high frequency sampling schemes can be very useful.
- High frequency sampling of emissions produces data sets that show strong autocorrelation patterns both on hourly and daily basis. From a statistical point of view independent observations that are derived from a restricted number of sampling intervals randomly distributed in time, can be as informative as high numbers of autocorrelated observations based on continuous sampling.
- Sampling periods in the GL protocol are restricted to one specific summer and one specific winter period. A more reliable and unbiased estimate of the yearly mean can be derived by randomly sampling over the whole year instead of restricted periods.
- Measuring instruments should at all times be unbiased, i.e. systematic measurement error should be avoided. However, random measurement error is of much less importance as it can easily be downscaled by the number of replications in the sampling scheme (k x l x m).

TOWARDS A NEW APPROACH: MULTI-SITE SAMPLING

In 2004 an update of the ammonia emission protocol was commissioned that should make use of all new insights and experiences since the introduction of the GL protocol. This initiative was initiated by the earlier completed update of available measurement principles and instruments for the emission of gaseous compounds from livestock facilities carried out by a special working group (Mosquera et al., 2002; Mosquera, 2007). This initiative was also related to the first preliminary results of the extended statistical analysis on ammonia emission datasets (Mosquera and Ogink, 2004) that were made available to the technical working group that coordinates the assignment of ammonia emission factors. Both information sources offered the opportunity to drastically redesign the sampling strategy and make use of a wider range of measurement instruments. In addition to the modification of the ammonia protocol, new regulatory developments since 2006 asked for the definition of similar protocols for emissions of odor, PM10, methane and nitrous oxide. The completion of these protocols have been synchronized into one review and approval process. Drafts of these protocols have been approved and the final versions will be published before summer 2008. The main characteristics of the modified approach for ammonia emissions can be summarized as follows:

- Sampling will take place at four representative farm locations, i.e. k = 4. By doing so the overall accuracy is improved by a factor 2, compared to the earlier design of the ammonia protocol where one farm location was sampled.
- Instead of mandatory high frequency sampling over extended periods, a restricted number of 24 hour cumulative sampling periods is introduced, during each of which the mean ammonia concentration of ventilated air and the mean ventilation rate has to be determined. Diurnal variations are eliminated by sampling over 24 hours.
- For cumulative sampling over 24 hours the use of impingers setups is allowed, in which a known air flow is led through a series of washing bottles with acid solution that traps the ammonia. Impinger measurements are relatively simple, low cost and accurate.
- The number of independent sampling events on each farm location was set at six, i.e. l = 6. Sampling events are distributed over one year, being randomly taken in subsequent two month periods. By this procedure seasonal variations that influence concentrations and ventilation rates throughout a year are equally distributed and well balanced in the sampling scheme. For housing systems with production cycles that affect emission patterns, like broilers or fattening pigs, it is prescribed that measurements are equally divided over the growing period. Similarly, in cases where regular management practices can be expected to affect emission levels, care should be taken that these practices are incorporated in the sampling scheme in such a way that samplings are well distributed over these management practices. Sampling six times at one farm location was considered large enough to deal with the within-farm location variance and at the same time ensures that observations were sufficiently spread in time to be independent from each other.
- Ranges for critical management factors (like feed composition) are updated according to what is considered standard management.
- The number of measurement methods that can be used for determining the air flow is expanded, mainly using the array of methods described by Mosquera et al. (2002). This modification is especially of importance for animal housings with natural ventilation systems.

In practice emission measurements on farm locations will in many cases include all relevant emission components, such as ammonia, odor, greenhouse gases and PM10. Both for reasons of cost efficiency and for the interest of funding parties, measurements of different emission components are normally combined. This means that there is a practical need to harmonize the sampling scheme of these components, unless there is a very compelling technical reason to apply another scheme. As demonstrated for odor and ammonia, it is expected that the emissions of PM10 and greenhouse gases is also subject to considerable variation between farms. For these reasons, the ammonia emission sampling scheme is utilized in the protocols for the other gaseous compounds.

CONCLUSION

The multi-site approach basically represents a shift from intensive long term measurements on one site to less frequent sampling on more farm sites. It recognizes the importance of the earlier neglected variance layer that represents farm variations as a result of different farm management practices. The multi-site approach at the same time allows for a much less intensive and less costly measuring effort at each of the locations. The multi-site sampling strategy is mainly based on the interpretation of variation patterns that were analyzed for low emitting housing systems with modified pen designs and manure removal techniques. It is quite well possible that for other groups of mitigation measures, like for example the efficiencies of air purification techniques, variation patterns differ. The new protocol framework in principle allows for modifications of the sampling strategy in case of specified groups of measures. Such modifications have to be justified on basis of analysis of emission measurements where these measures are applied, and will be attached as special cases to the general protocol. This procedure automatically facilitates the use of new findings from the learning by doing process and is in line with our observation that measurement protocols should be designed on basis of knowledge of the variance behavior in real world practice.

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Conference Funding Support Provided by:

Iowa State University, College of Agriculture and Life Sciences and University Extension
USDA National Research Initiative Project: Air Quality Extension and Education
Iowa Egg Council
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ISBN 978-0-9817781-0-5