# An Evaluation of Alternative Approaches to Reduce Odors from Intensive Swine Operations
# -   Interim Report -

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*Item #428, 1999 Appropriations Act*

# EXECUTIVE SUMMARY

## Introduction

The increasing size of swine production facilities, coupled with human housing growth in rural farming areas, has resulted in many odor complaints. Odor has been shown to be a very subjective problem. Both the ability to smell and the perceived offensiveness of a given odor vary widely from person to person.

## How do we sense and measure odor?

There are two general approaches to measuring odor: 1) to measure the concentration of specific gases in an air sample, and 2) to use the human nose to perceive odor. Unfortunately, these two approaches are not well correlated, i.e., the results from gas concentration measurements do not predict the results that will be obtained from a group of trained human sniffers.

When measuring odor, what one hopes to quantify is the human response to the stimulus. If a chemical compound, or group of chemical compounds that is easily measured and correlates well with the response of an odor panel were identified, it could be used as an indicator of odor. Unfortunately, no "short list" of compounds, whose concentrations correlate with readings obtained from an odor panel, has been identified.

## What are States Doing to Regulate Odor Emissions?

Ten states have regulations directly limiting odor emissions from CAFOs. Thirty-four other states were found to have some regulation designed to curtail odor emissions without explicit limitations. Virginia falls into the latter category, with a required setback distance of 200 feet, and a general and individual permitting process that mandates environmentally-responsible manure management.

## What Are The Primary Odor-Causing Compounds Associated With Swine Production?

Over 168 chemical compounds have been identified in the air within swine confinement buildings. Some of the main odorous compounds are ammonia, amines, sulfur-containing compounds, volatile fatty acids, indoles, skatole, phenols, alcohols, and carbonyls.

## Do Air Emissions From Swine Facilities Represent A Threat To Human Health Or The Environment?

It appears that volatile organic compounds from swine facilities may affect the health of facility workers with primary complaints being eye, nose and throat irritation, headache, and drowsiness. It is not known if concentrations downwind from facilities are sufficient to affect the health of neighbors of livestock operations. More research is needed to establish air quality guidelines based on possible health effects.

## What Are The Main Sources Of Odor In Swine Production?

Three main sources of odors have been identified: the production facility, waste treatment and storage facilities, and land application. A study showed that approximately 50% of all odor complaints were as a result of land application of waste, with the remaining complaints split 20% to waste storage and 30% to the production buildings. The bottom line is that odor production can be reduced by instituting good housecleaning and management practices for the manure handling system and in the animal housing.

## Technologies Designed to Reduce Dust

Several technologies have been proposed to reduce dust levels, including sprinkling with oil, filtering the air, using washing walls and other wet scrubbers, and ozonation. For naturally ventilated buildings, where other dust-reduction technologies such as air scrubbers, biofilters and windbreak walls cannot be employed, oil spraying may be the best available solution for odor control. Washing walls can be retrofitted to houses with mechanical ventilation, and do not require a change in the existing fan system. They work well during low ventilation rates, but are relatively ineffective during periods of high ventilation. While several companies have attempted to market ozone systems for odor control in confined livestock housing, little has been published that documents the effectiveness of these systems. If claims of reduced disease and mortality, and/or improved growth and feed conversion efficiency are experimentally demonstrated and documented, ozone may prove beneficial to the hog industry.

## Technologies Designed To Treat The Air After It Exits The Building

Installation of biofilters and windbreak walls can be effective in reducing odor and dust in air. Biofilters may be employed in any application where odorous air is being mechanically ventilated, such as livestock housing, ventilated manure pits, and covered and ventilated lagoons. Biofilters, when operating properly, have been shown to be extremely effective (90%) in reducing odors from an air stream. Unfortunately, the energy required to push air through a biofilter is greater than design requirements for mechanically-ventilated production facilities, which means the fan system would have to be changed in order to implement biofilters.

Windbreak wall structures placed a few fan-diameters downwind of tunnel-ventilated production houses may help reduce dust and odor levels off-site of the facility. Windbreak walls are relatively inexpensive, can be easily retrofitted to an existing operation, and do not require significant maintenance. While windbreak walls may reduce nuisance complaints from neighbors, they do not mitigate the pollutant, and as such, would appear to represent a short-term fix.

## Waste Treatment and Storage

Technologies available to reduce odors from waste storage and treatment facilities can be classified in two groups: 1) technologies intended to be added to or to retrofit existing systems or 2) technologies designed to completely replace existing systems. Retrofit technologies are the most likely candidates for existing operations where a great deal of capital is already invested in the existing system. For future facilities or expansion of existing facilities, new waste storage/treatment systems may be justified.

### Retrofits to Existing Technologies Designed to Treat Waste and/or Reduce Odors from Waste Storage

**Covers.** One method to reduce the odor emitted from open manure storage facilities is to contain the odor and gases inside a cover. Low-cost organic materials appear feasible for small waste storage facilities, but are unlikely to work for large lagoons and may actually increase the waste loading if the organic material sinks into the lagoon. More expensive synthetic covers can effectively reduce odor emissions from large lagoons.

**Pit Additives.** Pit additive products can be grouped into categories according to their mode of action: masking agents; counteractants; absorbents; and chemical deodorants.

While the concept of a pit additive to reduce odor is very attractive, the efficacy of the products remains questionable. Based on extensive tests conducted by Purdue University, some products appear to reduce odor dilution threshold, but similar results would be expected one time out of four based on random chance, without any affect from the product.

**Liquid/Solids Separation.** Effective solid-liquid separation of fresh liquid or slurry manure will potentially offer the benefit of odor reduction in the liquid manure storage pits (or tanks) or anaerobic lagoon. Solid-liquid separation can also improve the economics and/or performance of the subsequent liquid manure treatment. Solid-liquid separation processes include sedimentation, screening, centrifugation, and filtration. The degree of odor reduction will depend upon the performance of the separator and the handling of the resulting solids.

### Technologies Designed to Treat Waste and/or Reduce Odors from Waste Storage

Waste treatment technologies are generally classified as aerobic (in the presence of oxygen) or anaerobic (without oxygen).

**Anaerobic Systems.** Most swine operations in Virginia employ an anaerobic lagoon to both treat and store the waste. If they are properly designed and operated, anaerobic lagoons can successfully treat manures. Nutrients will be stored in the sludge layer within the lagoon.

Anaerobic digesters can significantly reduce odor emissions, and in some cases may be less costly than a lagoon system.  Digesters are most likely to be cost effective in larger operations where there is sufficient on-farm energy demand to use the biogas produced.

**Aerated Systems.** In contrast to the anaerobic processes, aerobic systems have some level of free oxygen present.  In this reaction, many of the organic compounds related to offensive odors are minimized.  There are various strategies for aerated manure treatment including batch or continuous, operation at various temperatures, high or low aeration rates, suspending the microbial population in the waste or attaching it to a fixed film over which waste is directed.  Many aerobic treatment systems require trained personnel to operate.

## Alternative to Liquid Waste Systems

**Bedded Systems.** Most large-scale confined swine feeding operations use liquid manure handling systems.  Bedded systems create solid manure; the animals bed and dung on a deep bedded-pack of cornstalks, straw, or other materials.  The system shows advantages for odor control, pig health, and production.  Although gases and dust are emitted from solid or bedded systems, most people feel that odors from bedded systems are less objectionable than odors from liquid systems.  However, the systems are labor intensive, and highly dependent upon a reliable and affordable source of bedding material.

The costs for implementing the odor reducing treatment options discussed in the paper are summarized in the table at the end of the report.

# GASEOUS EMISSIONS FROM SWINE PRODUCTION FACILITIES: A REVIEW OF TECHNOLOGIES DESIGNED TO REDUCE ODOR

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## Introduction

The increasing size of swine production facilities, coupled with human housing growth in rural farming areas, has resulted in many odor complaints, raising the following questions:

*Are gaseous emissions from swine facilities a threat to public health and the environment, or are they merely a nuisance?*

*What can be done to minimize gaseous releases, and at what cost?*

While much work has been done to “solve” the swine odor problem, many aspects remain unsolved. The solution is elusive for many reasons. First, odor has been shown to be a very subjective problem. Both the ability to smell and the perceived offensiveness of a given odor vary widely from person to person. Also, there are many complex volatile compounds present in swine manure; to date no one has identified a short list of compounds whose concentrations correlate well with human perceptions of the odor. In other words, scientists have not yet determined a list of chemicals in manure whose concentrations can be measured and used to determine offensiveness to humans.

Before technologies to reduce odors can be tested for efficacy and before odor emissions can be regulated, it is necessary to establish objective means of measuring odors. The research community is searching for a low cost method of odor measurement that can be conducted rapidly, on-site.

## How do we sense and measure odor?

An odor is a sensation that occurs when a chemical impacts the human sensory apparatus—the nose. There are two general approaches to measuring odor: 1) to measure the concentration of specific gases in an air sample, and 2) to use the human nose to perceive odor. Unfortunately, these two approaches are not well correlated, i.e., the results from gas concentration measurements do not predict the results that will be obtained from a group of trained human sniffers.

Olfactometry

Odor sensing using the human nose in the form of a trained odor panel is called olfactometry. Several odor parameters can be collected. They include the following:

- **Odor thresholds**, defined as the ratio of odorous-to-clean air where detection or recognition occurs.
- **Odor intensity**, which is a measure of the strength of the odor. The strength is compared of an odor sample is compared to a set of known concentrations of n-butanol, a standard reference chemical (ASTM, 1988). The odor intensity is then expressed in parts per million of n-butanol or converted to an intensity scale. Different scales have been reported, including 0 to 3, 0 to 5, and 0 to 10.
- **Hedonic Tone**, which is a subjective judgment of the pleasantness or unpleasantness of an odor. It is rated on a scale of –10 to 10 where a score of –10 is extremely unpleasant, a 0 is neutral, and a 10 is extremely pleasant.
- **Odor sensation**, which is reported as a set of sensation descriptors including itching, tingling, warm, burning, pungent, sharp, cool, and metallic.
- **Odor descriptors**, which panelists select from a reference list. Different lists exist, but common categories include floral, fruity, vegetable, earthy, offensive, fishy, chemical, and medicinal.

Two methods of presenting samples to panelists are used—dynamic and static. As the names imply, dynamic olfactometry involves presenting the samples in a forced air stream while static olfactometry involves collecting samples on cotton swatches and presenting them in glass bottles, which the panelist opens and sniffs.

**Dynamic Olfactometry for Odor Measurement.** For dynamic olfactometry, a vacuum pump is used to collect samples of odorous air into non-adsorbing bags (such as Tedlar®), which are taken to an odor laboratory. Using a machine called an olfactometer, the odorous sample is mixed with a clean air sample in known proportions of clean-to-odorous air and presented to a panel member in a forced air stream. The most common presentation is called triangular, forced choice. The panel member is presented with three forced-air samples; two of the samples are clean air and one is clean air mixed with the odor sample. The panel member is asked to identify which sample is different. If they cannot detect a difference, the percentage of odorous air in the sample is increased, they are presented with another set of three air streams, and again asked to identify which of the three air streams is different. The presentation always starts with very dilute samples and increases the percentage of odorous air until an odor is perceived. The ratio of clean-to-odorous air where the panel member detects an odor is known as the detection threshold. This ratio of clean-to-odorous air is assigned units of measure called odor units (OU). For example, if the participant in an odor panel detects a difference in a mixture of 100 milliliters of clean air to 1 milliliter of odorous air, the odorous air would be rated at 100 OU. If the difference was detected when 200 milliliters of clean air was mixed with 1 milliliter of odorous air, the odorous air would be rated at 200 OU. Note: the more dilution with clean air that is required, the greater the OU of the sample, implying that the sample was more odorous.

Another threshold value that is often determined is the ratio of clean-to-odorous air where the panelist can first recognize the odor (i.e. can acknowledge that it "smells like" something.) This ratio of clean-to-odorous air is known as the recognition threshold. The recognition threshold often requires five to ten times more odorous air in the sample than the detection threshold. The odor recognition threshold is also reported in odor units (OU.)

Because odor perception is a highly subjective sensory response that involves not only physiological but also psychological reactions, it is important that an odor panel contain "representative" members that are trained. (Powers et al., 2000). Even when great care is taken to ensure panelist objectivity, it is impossible to remove all subjectivity and account for psychological influences such as mood and apathy towards participation on a particular day. In an attempt to standardize panel response, the American Society for Testing and Materials (ASTM) and the European Union (CEN prEn13725) reference perceived threshold values to an n-butanol standard (Sneath et al., 2000). This is accomplished by testing panel members using the n-butanol standard before exposing them to actual odor samples. If their ability to detect the n-butanol standard is not within a specified range on a given day, the panel member is rejected for that session.

Olfactometry is an expensive process, requiring the following:

1) an instrument capable of accurately mixing samples to create known ratios of clean-to-odorous air;
2) a room that is free of ambient odors and other sensual distractions;
3) a trained panel of at least five subjects available as needed; and
4) sampling equipment.

Commercial laboratories are available for analyzing samples by olfactometry; the typical price per sample is $175 plus shipping, sampling bags and sampling equipment. Depending on the number of samples collected, a final cost of approximately $250 per sample is representative.

**Static Olfactometry Odor Sensing**. With static olfactometry, odor samples are collected by exposing a cotton swatch to the odor source for an extended period of time. Swatchs are then placed in amber glass jars with teflon-coated lids and iced to 4C for transport to the odor panel. Ideally, samples are processed within 24 hours of collection.

To process a sample, the jar is allowed to reach room temperature and then opened and the air in the headspace is sniffed. Panel members rate the odor for intensity (either referenced to known concentrations of n-butanol, or by using a rating scale such as none at all, very weak, weak, moderate weak, moderate, moderate strong, strong, very strong or maximal), irritation intensity (none, every weak, weak, moderate weak, moderate, moderate strong, strong, very strong, maximal), and pleasantness (extremely pleasant, very pleasant, moderately pleasant, slightly pleasant, neither pleasant nor unpleasant, slightly unpleasant, moderately unpleasant, very unpleasant, or extremely unpleasant). Static olfactometry is less costly than dynamic because it does not require the mixing instrument.

**Scentometry.** Another method of odor sensing which employs the human nose is called scentrometry. A scentometer is a hand-held device that allows odors to be evaluated on site. The principle of operation is similar to a dynamic olfactometer. The scentometer mixes sample air with odor-free air (created by filtering the air through charcoal) in known proportions. The mixing is accomplished by changing the hole size through which odorous air travels while holding constant the hole size for odor-free air . The number of dilutions available depend on the scentometer, but a typical six-hole unit would allow dilution ratios of 2, 7, 15, 31, 170 and 350 parts odor-free to odorous air. The objective, similar to dynamic olfactometry, is to find the dilution ratio where an odor is first detectable.

The advantages of scentometry are that it is economically attractive and readings are taken on site. Disadvantages include odor fatigue because it is difficult not to expose the sniffer to the ambient environment (which is often odorous) before the scentometer is used, lack of dilution options, and inability to rate sniffers against their ability to sense a known reference concentration. Since this test is conducted on site, some concern has been expressed regarding a sniffer's ability to remain objective when they are seeing sources of odor emissions.

Tracer Compounds And Odor Indicators

When measuring odor, what one hopes to quantify is the human response to the stimulus. If a chemical compound, or group of chemical compounds that is easily measured and correlates well with the response of an odor panel were identified, it could be used as an indicator of odor. Unfortunately, at the present time, the use of a single compound, such as ammonia or hydrogen sulfide, for odor quantification is not recommended. Likewise, no “short list” of compounds, whose concentrations correlate with readings obtained from an odor panel, has been identified.

Hydrogen sulfide and ammonia are the two constituent compounds in the odorous air from livestock production facilities that are most often measured and reported. Unfortunately, several studies have shown poor correlation between the concentration of these two compounds and the odor intensity. While no list of chemicals from swine manure has been identified that correlates well with the readings of an odor panel, scientists are still attempting to identify the actual compounds that make up air emissions from swine production facilities.

### Gas Chromatography-Mass Spectrometry

Gas chromatography and mass spectrometry (GC-MS) are two technologies that allow identification and quantification of specific compounds, often in concentrations as low as parts per trillion. In gas chromatography, a sample is vaporized and injected into a stream of carrier gas moving through a column containing a stationary phase composed of a liquid or particulate solid. The sample is separated into its component compounds according to their affinity for the stationary phase. Mass spectrometry, which employs a specific detection system as part of a gas chromatograph, separates various compounds according to their mass and charge. While GC-MS does allow for identification of many compounds, the gas chromatograph is limited by the number of configurations (detectors, oven temperature, etc.) and columns that can be employed simultaneously. This limits the compound identifications to groups of compounds rather than a complete analysis of everything that might be present in a single sample. However, as the compound groups most responsible for malodor are identified, the ability to configure systems for optimal analysis is improved.

While GC-MS holds promise as a basic research tool for odor analysis, it is neither inexpensive nor portable. Also, to date, no one has been able to develop an odor dilution threshold prediction equation based on levels of compounds observed by GC-MS. In other words, the concentration of chemicals observed using GC-MS does not correlate well with the dilution levels required for detection of an odor by a human panel using olfactometry. Several reasons for the lack of agreement have been suggested (Powers et al., 2000):

1) dust is filtered from samples prior to olfactometry and this may remove many odorous compounds that GC-MS is identifying;
2) panelists may be responding to compounds not identified because the human detection threshold is lower than that of an instrument; and
3) there is a large variance between individuals on an odor panel that would not be accounted for by a prediction equation.

### Electronic Nose

Neither human odor sensing nor GC-MS are ideal solutions to odor monitoring. Both are expensive and generally neither are done on-site in real time. Certainly neither can be accomplished on a continuous basis to observe how odor emissions fluctuate over time. A portable electronic nose, capable of reproducing the response of a trained odor panel would be a very useful measuring device.

Electronic noses are used in the food and beverage industry for quality control purposes (Persaud, 1992). However, the electronic nose has not yet reached commercial manufacture for odor sensing of agricultural wastes.

The key component of an electronic nose is an array of gas sensors that respond to various volatile organic compounds (VOCs), the primary odorous constituents that generate the characteristics of specific odors. The next component is the sampler unit that transports the odorant from a sample collection device to the sensor array. Finally, a signal processing system accepts the sensor array output for analysis. The output of the electronic nose can be the identity of the odorant, an estimate of the concentration of the odorant, or the characteristic properties of the odor (such as intensity, hedonic tone, sensation, etc.) as might be perceived by a human panelist.

While the human nose has a very large number of odor receptors (greater than $10^8$), the electronic nose typically has 5 to 32 sensors. The human nose has thousands of receptor types while the electronic nose has only a few. The receptors in the human nose send their information to a multilevel neural network that responds within seconds to identify and characterize the odor produced by the sample. Currently available electronic noses take several minutes to capture the information, process it, and respond. The human nose is sensitive in the range of parts per trillion, while the electronic nose can only sense in the high part per billion or part per million range. Finally, while the receptors in the human nose regenerate spontaneously every few weeks, the sensors in an electronic nose must be replaced on a maintenance schedule. (Nagle et al., 1999)

In a lab prototype, Nagle demonstrated that a calibrated electronic nose could reproduce the response of a trained odor panel. While these results are promising, a commercial model has yet to be developed.

## What Constitutes An Odor Nuisance?

Odor nuisances are generally determined by four factors: **f**requency, **i**ntensity, **d**uration, and **o**ffensiveness. Frequency refers to how often the odor is detected; intensity refers to the strength of the odor; duration refers to how long the odor occurrence persists, and offensiveness refers to the character or hedonic tone of the odor (how pleasant or unpleasant it is). These are sometimes referred to as the “FIDO” factors. How much someone is disturbed by an odor depends on all four factors. Generally, even an intense and offensive odor can be tolerated if its occurrence is infrequent and the duration of an occurrence is short. The more intense and offensive the odor, the less often its occurrence is likely to be ignored. A noticeable odor that is not terribly offensive may upset someone who is exposed to it often and for significant duration.

## What are States Doing to Regulate Odor Emissions?

Redwine and Lacey (2000) conducted a survey of states to determine regulations pertaining to odor emissions from confined animal feeding operations (CAFOs).

They reported that ten states have regulations directly limiting odor emissions from CAFOs. Thirty-four other states were found to have some regulation designed to curtail odor emissions without explicit limitations. Virginia falls into the latter category, with a required setback distance of 200 feet, and a general and individual permitting process that mandates environmentally-responsible manure management.

Of the ten states with explicit odor limits, six specify an allowable detection threshold at some location such as the property line of the operation or the effected business or dwelling; the allowable detection thresholds vary from 2 to 15. Rhode Island and Vermont “prohibit emission of objectionable odors beyond the property line,” (Redwine and Lacey, 2000). South Carolina states that “no producer may cause, allow or permit emission of an undesirable odor into the ambient air unless preventive measures to abate/control the odor are utilized.” Finally, Washington requires that “any person that allows the emission of an odor must use recognized good practices to minimize the odors; masking is not allowed.” All ten states are basing odor limits on human perception; none have specified limits based on analytical measurement of odorous compounds.

Of the 34 states with implicit odor regulations, ten employ setback distances, which are generally a function of animal numbers and species. Distances reported (Redwine and Lacey, 2000) vary from a low of 50 ft in Arkansas to a high of 16,000 ft in Kansas. Several states require odor control plans as a part of a pollution abatement permit.

## What Are The Primary Odor-Causing Compounds Associated With Swine Production?

Over 168 chemical compounds have been identified in the air within swine confinement buildings (Mackie et al., 1998) Some of the main odorous compounds are ammonia, amines, sulfur-containing compounds, volatile fatty acids, indoles, skatole, phenols, alcohols, and carbonyls. Many of the odorous compounds are the result of anaerobic (without oxygen) microbial decomposition of manure and wasted feed.

Two odorous compounds that receive a great deal of attention are ammonia and hydrogen sulfide. There are two forms of ammonia in solution: $NH_3$, which is a non-ionized gas and $NH_4$, which is the ionized form. The relative proportion of each depends upon the pH. Virtually all of the ammonia in animal waste has the potential to be lost as $NH_3$ gas. In addition to being an odor problem, ammonia gas release is increasingly being considered an environmental problem, because it tends to be oxidized by various oxidants in the air to produce nitrous oxides, which are considered major contributors to acid rain. The release of ammonia is severely restricted in some parts of the world. (Xue et al., 1998)

Hydrogen sulfide ($H_2S$), which is produced by anaerobic microorganisms that convert sulfate in manures to sulfide, is considered the characteristic odor of livestock urine. It is a highly toxic and malodorous gas that can reach levels that are threatening to livestock and humans. Exposure to a few minutes of hydrogen sulfide concentrations of 2000 ppm has proven fatal to humans. In addition, animals exposed to sub-lethal doses may become more susceptible to pneumonia and respiratory diseases.

## Do Air Emissions From Swine Facilities Represent A Threat To Human Health Or The Environment?

Federal air quality standards are designed to protect human health and the environment. Currently, there are no federal standards for odor emissions. Similarly, no federal emissions standards have been set for regulating livestock industries. However, the literature implies that there could be human health effects from livestock odor emissions.

According to Schiffman (1998), there are four possible mechanisms by which odor releases from swine production facilities could affect human health:

1. The volatile organic compounds (VOCs) could cause toxic effects;
2. The odorant compounds could cause irritation in the eyes, nose and throat;
3. The VOCs could stimulate sensory nerves to cause neurochemical changes that potentially influence health; and
4. Health effects could be due to cognitive and emotional factors.

Complaints of health effects from odors associated with livestock operations probably derive from a combination of physiological and psychogenic sources (Shiffman, 1998.) Shiffman (1998) reports that, according to the rules of classical neurotoxicology, it is unlikely that any individual compound released from swine facilities will be of sufficient concentration to be toxic to neighbors of swine facilities. However, it is not yet known if **mixtures** of compounds released from production facilities have the potential to be toxic.

Hudnell et al. (1992) exposed healthy males to a mixture of 22 VOC with a total concentration of 25 $mg/m^3$. Subjects experienced irritation of eye and throat, headaches and drowsiness. They concluded that the responses were not psychosomatic but were caused by stimulation of free nerve endings in the nose and throat by subthreshold levels of VOC that interacted additively or hyperadditively.

Donham et al. (1990) found that 87% of workers in swine confinement buildings reported work-related cough due to exposure inside livestock buildings. Total dust and ammonia are two primary environmental predictors of decreases in pulmonary function over a work period. Reynolds et al. (1996) suggested allowable exposure limits for occupational exposure of swine workers at 2.5$mg/m^3$ total dust and 7.5 ppm of ammonia. Due to dispersion, dust and ammonia levels experienced downwind of a swine production facility are generally lower than these suggested limits. However, Thu et al. (1997) found that neighbors of a large-scale swine operation reported experiencing more symptoms associated with respiratory inflammation than demographically-similar control subjects living near little-to-no livestock production.

Schiffman et.al. (1995) measured moods of residents living near large-scale hog operations and a control group matched according to gender, age, race and years of schooling. They found a significant difference in mood between persons exposed to swine odor and those who were not. The exposed group reported significantly more tension, depression, anger, fatigue and confusion than the control subjects. Other medical research has shown that impaired mood and stress may influence health via biological mechanisms that include immune changes.

It appears that VOC from swine facilities may affect the health of facility workers with primary complaints being eye, nose and throat irritation, headache, and drowsiness. It is not known if concentrations downwind from facilities are sufficient to affect the health of neighbors of livestock operations. More research is needed to establish air quality guidelines based on possible health effects (Schiffman, 1998).

## What Are The Main Sources Of Odor In Swine Production?

Three main sources of odors have been identified: the production facility, waste treatment and storage facilities, and land application. A study conducted in the United Kingdom (Hardwick, 1985) showed that approximately 50% of all odor complaints were as a result of land application of waste, with the remaining complaints split 20% to waste storage and 30% to the production buildings. While the data are old, general observations in the United States would confirm these findings. However, with incorporation of wastes at the time of land application, or the spreading of lagoon effluent (as opposed to manures), odor from land application, a higher percentage of complaints are likely to come from the production facilities or the manure storage facilities.

Researchers at the University of Minnesota (Jacobson et al., 2000) collected and analyzed air samples from over 260 sources on nearly 80 farms in Minnesota. They combined the odor concentrations measured with ventilation rate data to produce odor emission rates for animal buildings and outdoor manure storage units. Their data for swine are reproduced below:

Emission Rate Data For Swine Buildings (Jacobson et al., 2000)

| Animal Type | Housing Type | Emission Rate ($OU/s/ft^2$) |
|---|---|---|
| Finishing, gestation or nursery | Deep pit or pull plug, natural or mechanical ventilation | 0.65 |
| Finishing, gestation or nursery | Cargill (open front) with open concrete lots | 0.84 |
| Farrowing | Flush, mechanically ventilated | 0.28 |
| Finishing, gestation or nursery | Deep bedded hoop barn | 0.19 |

Emission Rate Data for Swine Manure Storage (Jacobson et al., 2000)

| Storage Type | Emission Rate ($OU/s/ft^2$) |
|---|---|
| Earthen basin, single cell | 2 |
| Earthen basin, 1st cell | 2 |
| Earthen basin, 2nd cell | 0.8 |
| Anaerobic Lagoon, 1st cell | 0.4 |
| Anaerobic Lagoon, 2nd cell | 0.1 |

These data were incorporated into an air dispersion model to predict the frequency of odor occurrences at various distances from production facilities. The measured odor emission rate for each component of an operation is multiplied by the area of the component and then by a scaling factor. Based upon model calibration, Zhu et al. (2000) determined that emissions from animal production buildings and waste storage facilities needed scaling factors of 35 and 10 respectfully. This implies that the odor production from buildings is 3.5 times greater per unit area, if the emission number is the same. Since lagoons occupy significantly more area than production buildings, their contribution to the odor problem can be significant, even if their emission rate is relative low. The actual contribution of odor from the production facility, waste storage and land application aspects will vary from one production model to another.

Production Facility

Modern swine production typically separates production into four phases—gestation and breeding, farrowing, nursery, and finishing. It is unusual for a modern operation to participate in all aspects of production; most producers today specialize in one aspect of production. Facilities for each aspect differ and therefore, odor emissions and solutions may also vary for different aspects of production. However, there are basic strategies for minimizing odor production that apply to all aspects of production.

For all production phases, it is important to move manure away from animals (body heat will release odors from manures). Slotted floors that allow manure to fall away are less odorous than solid-floored buildings. It is also important to remove manure, wet feed, and other odor-producing products from facilities on a frequent basis. The bottom line is that odor production can be reduced by instituting good housecleaning and management practices for the manure handling system in the animal housing.

Technologies Designed to Reduce Dust

Airborne dust, a common problem inside swine facilities, has been linked to both animal and human health problems. Since suspended dust particles often absorb toxic and odorous gases, the reduction of dust concentrations inside buildings may also lower the odor and gas emissions from the facility. Several technologies have been proposed to reduce dust levels, including sprinkling with oil, filtering the air, using washing walls and other wet scrubbers, and ozonation. Each of these technologies will be discussed.

**Sprinkling with oil.** Research has shown that daily sprinkling of vegetable oils or vegetable oil/water mixtures onto horizontal surfaces in swine facilities (including the animals themselves) reduces dust inside the building. Oil sprinkling has also been shown to reduce odor and hydrogen sulfide levels both inside the building and in the ventilation air (Jacobson and Johnston, 1998). Oil can be applied manually with a hand-held sprayer or automatically with a permanently installed sprinkler system.

Zhang et al.(1996) tested six oil application rates over a two-week period in a grower/finisher research unit. The application rates varied from 10 ml/m$^2$ sprayed daily to 40 ml/m$^2$ for the first two days, followed by 20 ml/m2 for the next two days, and 5 ml/m$^2$ for the remaining 10 days. They observed reductions in dust levels from 37 to 89%, compared to an unsprayed control treatment; the amount of reduction depended upon the application rate. The overall mean reduction of respirable and inhalable dust concentrations was 71% and 76%, respectively. In general, the higher the spraying rate, the greater the dust reduction. However, they observed that applying higher rates initially quickly reduced dust levels and less oil was required on subsequent days to maintain dust suppression.

Lemay et al. (2000) tested an oil sprinkling system over a seven-week period to simulate a complete finishing/grow-out cycle. Their system used fixed nozzles, thus reducing the high labor associated with manual spraying with a backpack sprayer. Their application rate followed the recommendation of the Midwest Plan Service (Zhang, 1997)—40 ml/m$^2$ were applied for the first two days, 20 ml/m2 for the subsequent two days, and 5 ml/m$^2$ over the remaining period. In addition, oil was not sprayed in the operator walkways. They observed a reduction in dust mass concentration of 87% compared to the control room, which received no oil.

Two draw backs of oil-sprinkling systems have been noted. First, they can create slippery walkways if the application rate exceeds 20 ml/m$^2$. However, this problem could presumably be overcome by not spraying operator walkways. Second, studies have documented that more labor is required to clean oil-sprayed facilities as opposed to conventional facilities at the end of a grow-out cycle.  While the addition of a degreaser cleaning agent to the power washer cleaning solution should reduce this problem, some additional wash time will probably be needed if the facility has been oil sprayed.

Paszek et al. (2001) modified a commercially-available water sprinkling presoak system to automatically sprinkle oil.  The presoak system is commonly found on curtain-sided barns.  Modifying the existing presoak system to spray oil significantly reduced the initial cost of the oil-spraying system.  When the oil-spraying system was tested, clogging of nozzles was experienced.  To solve this problem, a delay timer was added to the system to continue the flow of water for one minute after the oil injection, in order to flush oil from the lines.  In addition, a surfactant was added to the oil at a 5% solution rate by volume to enhance mixing of oil and water.  Finally, a water filter was added to the system to prevent nozzle clogging by mineral particles in the water.  The initial cost to add oil-spraying capability to an existing presoak system in a 1000-head finishing room was  $316.  Operating cost (for oil and surfactant) was reported at $0.58/pig space-yr.

For naturally ventilated buildings, where other dust-reduction technologies such as air scrubbers, biofilters and windbreak walls cannot be employed, oil spraying may be the best available solution for odor control.

Summary

Oil sprinkling has been demonstrated to reduce dust and odors from a production facility.  However, it is not yet a commercially-adopted practice, and as such, vendors of turn-key oil-spraying systems are not readily available.  System cost and labor requirements have not been documented on a commercial scale, with the exception of the Minnesota study (Paszek, et al. 2001), which involved modifying an existing presoak spraying system.

**Washing walls and other wet scrubbers.**  Wet scrubbing involves the use of water sprays to remove dust particles from the air.   Many industrial air pollution control systems use sprays to reduce odor and to scrub dust, ammonia, sulfur oxides, and nitrous oxides from polluted air streams. For reactions involving acidic pollutants, an alkali is usually added to the wet scrubber (Bottcher et al., 1999).

A wet scrubber design consisting of a recirculating, evaporative pad cooling system was tested by Bottcher et al. (1999). The wetted pad system was installed in a stud wall about 4 feet upwind of ventilation fans and downwind of the pigs in a tunnel-ventilated building.  This system reduced total dust levels as much as 65% at low airflow rates, typical of winter ventilation.  However, at high airflow rates, typical for maximum hot weather ventilation, less than 20 % reduction in dust levels was achieved. They observed reduced ammonia levels in the ventilation airflow of 67% at low ventilation rates; however, no reduction in ammonia levels was observed at medium or high ventilation rates.  Reductions in odor intensity, determined by a human panel, were similar to dust level reductions—about 15% at high ventilation rates. System performance was strongly affected by residence time of air during treatment. With only one-tenth of a second contact time at high (summer) ventilation rates, the wet pad scrubber was relatively ineffective.

The wetted-pad system can function with the existing fan system. Installation costs are approximately $5.70 per pig space for an 880 head finishing building (North Carolina Swine Odor Task Force, 1998). The main operating cost is the energy required for the 1-hp pump, which at $0.08/kwh, would be about $600/yr. Some maintenance and water treatment would also be required.

Innoventor Engineering, Inc., Maryland Heights, MO manufactures an air-scrubber for use on mechanically-ventilated agricultural production facilities. According to company literature, air samples before and after a scrubber were collected and analyzed by Iowa State University and reductions in odor and hydrogen sulfide of 80 and 81% respectfully. Reductions in ammonia emissions were negligible. This system can be adapted to existing fans and does not significantly effect the operating pressures (and therefore the air flow through the building). The scrubber retails for approximately $1,200 per fan, installed.

Summary

Washing walls can be retrofitted to houses with mechanical ventilation, and do not require a change in the existing fan system. They work well during low ventilation rates, but are relatively ineffective during periods of high ventilation, due to the limited contact time of odorous air within the wetted pad. Performance data for commercially-available air-scrubbers used for odor reduction in animal production systems is lacking. This technology could prove feasible and deserves further research.

**Ozonation.** Ozone is a powerful oxidizing agent and an effective natural germicide. It is a triatomic allotrope of oxygen ($O_3$), and its use for “air quality improvements” has been investigated for over 15 years (Keener et al., 1999). Ozone has been successfully used in removing odor from drinking water. Ozone reacts with other gases, changing their molecular structure. At low concentrations of 0.01 to 0.05 ppm, ozone has a fresh smell associated with it. When the concentration is high it begins to smell like an electrical fire.

The issue of health risk associated with exposure to ozone has been investigated by OSHA (1998), EPA (1997) and FDA (1998). A general consensus of these groups is that high ozone levels can cause harmful respiratory effects. The current OSHA exposure limit for ozone is 0.1 ppm for an 8 hour, time-weighted average exposure (OSHA, 1998).

Ozone can be injected into the air in the production facility, or into the storage lagoon. The use of ozone in the production facility is described in this section. Use of ozone in the storage system will be described later in this paper.

While several companies have attempted to market ozone systems for odor control in confined livestock housing, little has been published that documents the effectiveness of these systems. Two studies were found in the literature—one by Priem (1977) and a second by Keener et al. (1999), which was further monitored and described by Bottcher et al. (2001).

Priem (1977) conducted three grow-outs of pigs in which one group was reared in an ozonated environment and another in a standard environment. The ozone levels in the treated building ranged from 0.05 to 0.15 ppm. He found that ozone reduced ammonia levels in the swine barn by 50% during cold weather and by 15% during hot ventilation conditions. Using gas chromatography, he also determined that ozone broke down indole, a highly odorous organic compound. Priem also monitored the health of the pigs in his studies and concluded that "little or no influence on the state of health or behavior of the animals was observed, although one has the impression of the pigs being quieter in the ozone sty." At the conclusion of the experiment, the respiratory tracts of 37 normally-reared and treated pigs were examined by veterinarians and, even on a microscopic level, there were no differences found between the two groups of animals. Finally, Priem observed a slightly greater daily growth and feed conversion efficiency for the animals in the ozone-treated houses, but the differences were not statistically significant beyond the 20% confidence limit.

Keener et al. (1999) describes an ozone system installed at a tunnel ventilated, 1000-head swine finishing operation in North Carolina. There was an identical facility (owned and operated by the same producer) adjacent to the one with ozone, which did not have an ozone system. This non-ozonated building served as the control for their experiments. Ozone levels in the house were measured at 0 ppm at the end where the ozone entered, 0.10 ppm in the middle of the building, and 0.15 ppm at the end where the air exited. Under maximum tunnel ventilation, the ozonation system reduced the ammonia levels by 58% and the total dust mass at the exit fan by 63% compared to the non-ozonated building. The air residence time in the building was 48s.

Bottcher et al. (2001) reported on additional data collected from the same facility. Using gas chromatography, odorant concentrations on dust particles from both the ozonated and non-ozonated houses were determined. The ozonated facility showed statistically-significant reductions in concentration levels of several short chain fatty acids, as well as p-cresol. A trained panel of humans at the Duke University Taste and Smell Laboratory found significantly less odor in samples collected from the outlet of the ozonated building compared to samples collected at the outlet of the non-ozonated facility.

Scott Postma of Ozone Solutions provided the cost data presented in Table 1 for the ozone system that his company sells (personal communication, March, 2001).

Table 1: Costs associated with the ozone system distributed by Ozone Solutions, Sioux Center, Iowa.

| | 1000-head one-room finisher | 1600-head nursery |
|---|---|---|
| System Life Expectancy | 8 years | 8 years |
| System Cost | $8900 | $4700 |
| Operating Cost | $1.25/day | $0.50/day |
| Installation Cost | $500 | $250 |
| Yearly Maintenance Cost | $100 | $100 |
| Four Year Rebuilt Cost | $500 | $1000 |

Cost estimates of $10/pig space for finishing operations have also been suggested (Vansickle, 1999).

Summary

Ozonation systems, like oil-spraying, can be implemented in naturally-ventilated buildings. Also, if claims of reduced disease and mortality, and/or improved growth and feed conversion efficiency are experimentally demonstrated and documented, ozone may prove beneficial to the hog industry. However, to date, such studies have not been published. Without demonstrated health and/or production benefits, the initial system purchase and operating costs are likely to prevent widespread use of ozone in swine production facilities.

## Technologies Designed To Treat The Air After It Exits The Building

**Biofilters.** A biofilter is an air filter composed of organic materials. These materials support the growth of bacteria that biologically degrade odorous compounds. Biofilters may be employed in any application where odorous air is being mechanically ventilated, such as livestock housing, ventilated manure pits, and covered and ventilated lagoons.

The use of biofiltration as an odor reduction technique for livestock was investigated in Germany during the early 1980s (Zeisig, 1987). More recently, the effectiveness of biofilters to reduce odors from swine operations has been demonstrated by several researchers in the United States. (Nicolai and Janni, 1998a, 2000; Martinec et al., 1999) Nicolai and Janni, in a one year study of biofilters, (1999) observed reductions in hydrogen sulfide emissions of 88% and ammonia emissions of 50% from swine facilities. The average odor threshold reading in the air exhausted from the facility, collected over a one-year timeframe, was reduced by 81% by passing through a biofilter. In a second study by Nicolai and Janni (1998a, 1998b), conducted over a 10-month period, they observed similar reductions—82% for the odor threshold, 80% for hydrogen sulfide concentrations, and 53% for ammonia levels.

The media that the biofilter is made from must provide a suitable environment on which the bacteria can live and reproduce; biofilter media must have good moisture retention capacity and provide a source of nutrients for the bacteria. In addition, it is important that the biofilter material have good porosity so that it will not require excessive energy to push the odorous air through it. Finally, it is desirable that the material be locally available (to minimize cost) and have a long useful life (before it decomposes). Materials that have been used for biofilters include compost, soil, peat, wood and brush chips, and bark. Mixtures of these materials are also used. Gravel or other biologically inert materials are sometimes included in the mix to increase the porosity of the material.

Martinec et al. (1999) tested five different materials for biofilters—biochips (a material from a German company); a mixture of coconut fiber and fiber peat; a mixture of bark and chopped wood, pellets from a fine compost plus bark, and biocompost from garden waste. They observed average odor threshold reductions ranging from 60 to 81%, depending on material, with biochips and coconut-peat performing around 80% and the other materials achieving between 60 and 65% odor reduction.

The size of the biofilter is determined by both the amount of air to be treated and the odor intensity of the air. The biofilter must be of sufficient size to allow adequate contact time between the odorous air and the biologically active biofilm that grows on the filter media. Nicolai and Janni (1999) provide design equations for sizing biofilters for both swine barns with deep pit manure storage and for covered manure storage units. Units are typically quite large; for example, the volume of filter required for a 1,000 head finishing building would be 10,000 cubic feet. Due to their size, biofilters are generally placed outdoors and left open, exposed to the weather.

Biofilters can be constructed from relatively low cost materials. However, typical agricultural ventilation fans are selected to operate at relatively low air pressure differentials and will not provide adequate air flow if a biofilter is added. Therefore, to add a biofilter to an existing facility requires replacing the existing fans with new fans selected to deliver the required air flow at higher operating pressures. This requirement significantly increases the cost of biofilter installations. The energy costs to operate the fans will also increased due to the increased operating pressure. The filters require some maintenance (they must remain moist to support biological activity, they must be protected from rodents and other burrowing animals, and weeds and other plants must be kept from growing on the filter.)

Summary

Biofilters, when operating properly, have been shown to be extremely effective (90%) in reducing odors from an air stream. They may be employed anywhere as long as the air is forced through the filter. Unfortunately, the energy required to push air through a biofilter is greater than design requirements for mechanically-ventilated production facilities, which means the fan system would have to be changed in order to implement biofilters. Janni et al. (2001) estimate the cost of installation of a biofilter at $100 to $150 per 1000 cfm fan capacity. The annual operating and maintenance costs, which include increased energy costs for the ventilation fans due to the filters, sprinkling costs to keep the filter moist, and cost to replace the media after five years. The authors note that both installation and operation and maintenance costs are highly variable.

**Windbreak walls**. Windbreak wall structures placed a few fan-diameters downwind of tunnel-ventilated production houses may help reduce dust and odor levels off-site of the facility. The walls block the fan airflow in the horizontal direction, which directs the odorous air stream upward where it mixes with the air stream over the building (Bottcher et al., 2000a). This can result in a larger (and less concentrated) air plume leaving the building. Windbreak walls also reduce the airflow rate at ground level on the leeward side of the wall, which, depending on facility layout, may reduce airflow over the lagoon. Airflow over a lagoon will pick up odor being emitted from the lagoon surface, so reducing the airflow over the lagoon can reduce odor emissions from the lagoon.

Windbreak walls consist of a frame and a covering. They can be built from different materials, but a major design consideration is assuring that they can withstand high winds. A windbreak wall may be designed to withstanding high winds or it may be designed to fail in a planned way. For example, designing the straps that hold the tarp to the frame in such a way that one side of the tarp will release (and therefore no longer resist the winds) will assure that the wall will not fail during storms.

Low-cost walls can be made from UV-resistant materials such as medium-density polyethylene, trampoline-quality tarpaulins, or aluminum roofing fastened to posts. The frame can be wooden or steel pipe and must be anchored to the ground so that it can withstand moderately high wind pressures. Windbreak walls do not add significant backpressure to ventilation fans, and therefore existing fans can be used and fan energy costs should not increase. The operating cost of a windbreak wall is comparably low, but periodic cleaning of odorous dust from the walls is necessary to control odor, unless rainfall is sufficient to clean them. Installation of windbreak walls is estimated to cost $1.50 per pig space (North Carolina Swine Odor Task Force, 1998).

The ability of windbreak walls to deflect an airstream upward has been demonstrated with scale models and observed at an installation outside an actual swine facility using smoke candles (Bottcher et al., 1998, 2000a, 2000b). Limited odor data, collected on-site using a scentometer, indicated some odor reduction.

However, only limited odor sampling has been conducted.  Studies to qualify windbreak wall efficiencies at odor abatement are on-going at North Carolina University (Bottcher et al., 2000b).

Summary

Windbreak walls are relatively inexpensive, can be easily retrofitted to an existing operation, and do not require significant maintenance.  However, their effectiveness at odor reduction has not been extensively demonstrated.  A significant disadvantage of windbreak walls is that they do nothing to actually treat or reduce odor emissions.  Their mechanism relies on the old adage, "dilution is the solution to pollution."  While windbreak walls may reduce nuisance complaints from neighbors, they do not mitigate the pollutant, and as such, would appear to represent a short-term fix.

## WASTE TREATMENT AND STORAGE

Waste treatment and storage is necessary to protect the environment from degradation.  Of particular concern are the following:

**Organic loadings to water bodies**.  (measured in terms of chemical oxygen demand (COD) or biological oxygen demand (BOD).  Organisms in the waters consume the organic matter and in the process consume oxygen, thus reducing the dissolved oxygen content of the body of water and threatening the well-being of fish, etc.
**Nutrient loadings to water bodies**.  Nitrogen and phosphorus can promote vigorous growth of aquatic plants.  When these plants ultimately decompose, they add an organic loading to the water body, thus reducing dissolved oxygen.
**Pathogens**.  Escherichia coli (E. coli), salmonella, giardia, campylobacter, and cyptsopridum parvum (C. parvum) are disease organisms that can be transferred from animals to humans.

While this review concentrates on the odor-reducing capacity of various storage/treatment systems, it is clearly important that animal wastes be treated for more than odor emissions.  Therefore, it is impossible to fully evaluate the merit of a waste handling system without considering all of its potential environmental impacts.  Likewise, selection of a waste system must be based on its ability to protect the environment, including air quality.

Technologies available to reduce odors from waste storage and treatment facilities can be classified in two groups:

1) technologies intended to be added to or to retrofit existing systems or
2) technologies designed to completely replace existing systems.

Retrofit technologies are the most likely candidates for existing operations where a great deal of capital is already invested in the existing system.  For future facilities or expansion of existing facilities, new waste storage/treatment systems may be justified.

Retrofits to Existing Technologies Designed to Treat Waste and/or Reduce Odors from Waste Storage

**Covers.** One method to reduce the odor emitted from open manure storage facilities is to contain the odor and gases inside a cover. By covering an outside manure storage pit or tank, the mass transfer of hydrogen sulfide and other volatile organic compounds from the liquid to the gas phase is reduced. There are several ways to cover a manure storage structure; each has advantages and disadvantages. A range of organic and inorganic cover materials, such as chopped straw, cornstalks, Leka rock (a porous material made from lava rock and coated with an impervious material that is baked on the surface), clay balls (also called artificial rock), and generated surface bubbles have been tried. Also, different methods of attaching the cover, or allowing it to float, have been suggested.

In two separate studies, Li et al. (1998) and Clanton et al. (1999) researched the effect of covering a manure surface with low cost materials, including both organic and inorganic cover materials. Materials investigated included chopped straw (applied at thickness of 10, 6 and 3 in), cornstalks (applied at thickness of 10 and 6 in), vegetable oil (applied at at thickness of 0.4 in), combination of straw/oil (12 inches thick), Leka rock (applied at thickness of 1.5, 3 and 6 inches), floating clay balls (8 inches thick), a PVC/rubber membrane, and a geotextile membrane. The researchers used small tanks—Li et al. ( used steel tanks, six-feet in diameter by 4 feet high with manure filled to a height of three feet. Clanton et al. (1999) used 200 gal polyethylene tanks to contain the manure. Covering materials were applied on the manure surface and odor concentrations above the covers and liquid manure surfaces were sampled and analyzed weekly using air samples.

Li et al. (1998) concluded that the thickness and type of cover material did effect odor emission and the integrity of the cover. 10-inch-thick wheat straw reduced odor emissions more than 90% over a nine-week study. The six-inch straw cover was also effective in controlling odor over the nine-week period, but there was variability from week to week in the odor reduction. A three-inch cover of straw also reduced the odor level, however, the surface of straw remained wet on this layer after the third week and flies were attracted to it. The Leka rock and clay balls were effective in controlling odor with little difference observed due to depth of application. Clanton et al. (1999) found odor reductions in the range of 60 to 80 % for all covers except the oil film. They reported that the oil film, when applied to the top of the manure, created its own offensive odor and therefore, they did not recommend its use. However, the addition of a layer of oil to a straw cover may increase its useful life. Because these tests were conducted on small tanks, their applicability to lagoons, which are often several acres in size, is questionable.

Jacobson et al. (1999) conducted a demonstration project to evaluate the performance of straw covers on actual on-farm manure storage units. Straw was blown on five manure storage units; both barley and wheat straw were used. Four of the storage units were earthen basins, one was an above ground tank. The earthen basins ranged in size from 0.2 0 to 1.5 acres. The ability to get the straw evenly distributed was a function of basin size; they reported having difficulty in getting the 1.5 acre facility completely covered. An application rate of approximately one large bale per 500 $ft^2$ was used by all participants to get a 12-inch depth of straw on the manure storage unit. They reported an average cost of the straw of $0.08/$ft^2$ ($3,500/acre), which did not include application costs. The length of time that the covers remained floating varied from six weeks to four months. Factors such as amount of rainfall, depth of storage unit, surface area and manure characteristics may explain some of the variations seen in cover life. The operators of the storage units were able to agitate and pump the straw out when the storage was pumped in the spring.

Leka rock, which has been shown to significantly reduce odor emissions and has lasted three years (and still going) on an above-ground swine waste tank on a research farm owned by Iowa State University. Cost for the material is about $150 to $180 per cubic meter delivered to the Midwest in bulk quantities. For a thickness of 1.5 inches, this represents a cost of $0.53/$ft^2$ or $23,130/acre. If a six-inch thickness was applied, the cost would be $2.12/$ft^2$ or $92,500/acre.

Odor Control Systems, Inc. (P.O. Box 2642; Shelby, NC. Phone: 866-464-7667) sells a patented, permeable lagoon cover that is anchored in a trench around the lagoon. The system has been installed on a 1.2 acre lagoon in North Carolina and is being evaluated by Duke University. The cover appears to provide significant odor reduction (greater than 90%). The newest generation cover has a twenty-year warranty and sells for about $1.35/$ft^2$ ($59,000/acre), installed (Ron Marsh, personal conversation, June 12, 2001).

Baumgartner Environics, Olivia, Minnesota sells an impermeable, floating cover, which they call BioCap™. According to their literature, 7.2 million square feet of cover has been applied to lagoons in eight states and Canada. Odor reduction due to the cover was evaluated by Dr. D. Bundy, while acting as a paid consultant. Bundy's report to the company, which is posted on their web site, (www.bei-ec.com) indicates that odor reductions from 70 to 90% on covered versus uncovered storage facilities were observed. The cover material sells for $0.14 to 0.22/$ft^2$ ($6,100-9,500/acre) installed, and has an expected life of three to five years.

<u>Summary</u>

Covering manure storages and lagoons can significantly reduce odor emissions. Low-cost organic materials appear feasible for small waste storage facilities, but are unlikely to work for large lagoons and may actually increase the waste loading if the organic material sinks into the lagoon. Synthetic covers can effectively reduce odor emissions from lagoons. The cost of a synthetic cover ranges from about $0.14 per square foot of surface area to more than $1 per square foot installed. The larger the storage, the less the cost per square foot, but the greater the total cost.

**Pit Additives.** Pit additive products can be grouped into categories according to their mode of action. Ritter (1989) identified five categories for odor control agents:

1) masking agents, which are mixtures of aromatic oils that have a strong characteristic odor of their own. They are designed to cover up, or mask the targeted undesirable odor with a more desirable one;
2) counteractants, which are mixtures of aromatic oils that cancel or neutralize the targeted odor such that the intensity of the mixture is less than that of the constituents;
3) Digestive deodorants, which contain bacteria or enzymes that eliminate undesirable odors through biochemical metabolic degradation processes;
4) Absorbents, which have a large surface area and are used to adsorb targeted odors before they are released or volatilized to the environment; and
5) Chemical deodorants, which are strong oxidizing agents or germicides that alter or eliminate microbial action responsible for odor production, or chemically oxidize compounds that make up the undesirable odor mixture.

The concept of adding a substance to manure, and thereby abating odor, is attractive; pork producers have expressed a great deal of interest in such a product. To date, there have been hundreds of commercial pit additive products brought to the marketplace. Unfortunately, the ability of these products to consistently abate odor is largely unproven. In an attempt to determine the efficacy of pit additives, the National Pork Board funded a study that tested thirty-five commercially-available products. The tests were conducted at by the Purdue University Agricultural Air Quality Laboratory.

The tests conducted at the Purdue Agricultural Air Quality Laboratory consisted of three testing periods of 42 days each. The reactors, which were made of rigid PVC, were 48 inches tall and 14.9 in inner diameter. The reactors were capped, and supplied with ventilation air at a rate of 0.25 cfm. Swine manure for the tests was collected from a commercial grow-finish operation in West Lafayette, Indiana. The manure had accumulated for approximately 19 days in the building collection pit, prior to collection for the pit-additives trials. Manure was added to the reactors every week (days 7, 14, 21, 28, and 35) during the trials. The additives were applied to the manure in the reactors according to the quantity, frequency, and procedures recommended by the manufacturers. Ammonia, hydrogen sulfide and carbon dioxide levels were measured six times daily for the first set of reactors, and three times daily for tests two and three. On days 5, 19, 33, and 40 odor samples were collected from each reactor and analyzed using forced-choice olfactometry to determine the odor detection threshold. Odor intensity, odor offensiveness (hedonic tone) and odor character were also determined by the odor panel. Finally, manure samples were analyzed at the beginning of each trial and then from each reactor at the end of each trial. Data collected on the manure samples included total solids, volatile solids, total suspended solids, chemical oxygen demand, pH, total Kjeldahl nitrogen, ammonium nitrogen, phenol, p-cresol, indole, skatole, and volatile fatty acids.

The test results for each product have been published (Tengman et al., 2001). Of all thirty-five products tested, none were statistically successful in reducing odor dilution threshold, hydrogen sulfide and ammonia; however, six products decreased two of the three indicators. Four products showed a statistically-significant (at the 75% certainty level) reduction of the odor detection threshold, with the reduction ranging from 25 to 32%. Ten products decreased hydrogen sulfide emissions, with reductions ranging from 14 to 47%. The statistical confidence in hydrogen sulfide reductions was high (95%) for seven of the ten products. The other three showed a 75% confidence of reducing hydrogen sulfide. Twelve products decreased ammonia production, with decreases ranging from 3 to 15%.

It should be noted that twenty of the thirty-five products tested reduced at least one of the factors (ODT, $H_2S$, $NH_4$) at a statistical confidence level of at least 75%. However, twenty-one of the products **increased** at least one of the factors at the 75% confidence limit. Often the reduction in one factor was accompanied by an increase in another. While only four products reduced the odor dilution threshold, nine of the products **increased** it; two of these increases were at the 95% confidence level. No product achieved greater than a 75% confidence level in decreasing the odor detection threshold.

Summary

While the concept of a pit additive to reduce odor is very attractive, the efficacy of the products remains questionable. Based on extensive tests conducted by Purdue University, some products appear to reduce odor dilution threshold, but only at statistically-low confidence levels (75%). A 75% confidence level implies that similar results would be expected one time out of four based on random chance, without any affect from the product. It should be noted that the tests conducted at Purdue University simulated pit storage. Similar tests simulating an anaerobic treatment lagoon have not been conducted.

**Liquid/Solids Separation.** The complex organic compounds in animal manures that release odorous compounds when they undergo anaerobic decomposition are contained within the manure solids. Therefore, effective solid-liquid separation that is capable of removing a substantial amount of organic solids from fresh liquid or slurry manure will potentially offer the benefit of odor reduction in the subsequent liquid manure storage pits (or tanks) or anaerobic lagoon. Solid-liquid separation can also improve the economics and/or performance of the subsequent liquid manure treatment. For example, reducing the organic loading rate reduces the size requirement of an anaerobic lagoon and reduces the oxygen demand in an aerobic treatment system. The separated solids can be utilized on farms near animal operations or can be economically exported to other areas as fertilizer and soil conditioning products (Zhang and Westerman, 1997).

Zhang and Westerman (1997) point out that most of the odor-generating compounds (carbohydrate, protein, and fat) and organic nutrient elements (nitrogen and phosphorus) are contained in fine particles. To effectively control odor generation and reduce the nitrogen and phosphorous content of the resulting liquid, removing particles smaller than 0.25mm in nominal diameter is necessary (Zhang and Lei, 1998). Separating fine particles from the liquid manure is a difficult tusk. Sedimentation basins and mechanical separators are the primary types of separation equipment used in livestock farms. Unfortunately, due to their relatively low separation efficiencies, their effectiveness on the odor and nutrient reduction in the liquid fraction is considered to be insignificant. Chemical treatment of manure may need to be considered to enhance the removal of organic solids and nutrient elements from the liquid manure (Zhang et al. 1998).

Solid-liquid separation processes include sedimentation, screening, centrifugation, and filtration. Sedimentation and screening are the most commonly used techniques for animal manure treatment.

<u>Sedimentation</u> is the most common farm application of liquid-solid separation. Sedimentation involves slowing down the flow velocity so that gravity will settle out the heavier particles. A retention time of 30 minutes is recommended in a sedimentation basin. Sedimentation basins are generally concrete consisting of a settling channel, which is a wide, shallow, gently sloping, flat-bottomed waterway in which runoff solids settle. Wastes settle from the slurry and the solids dry naturally. The channel is typically tractor-scraped so the bottom width is 10 feet or more. Sedimentation is most effective for treating dilute wastewater, such as flushed manure or runoff from feedlots (Zhang and Westerman, 1997). While sedimentation may not significantly reduce odor releases from the remaining liquid fraction, it is often employed to reduce clogging in nozzles use for land application of the effluent.

<u>Screen separators</u> have been used with animal manures and include stationary, vibrating, and rotating screen separators. Stationary screen separators employ a slow relative motion between the manure and the screen, which is mounted on an incline. The liquid/slurry manure is pumped to the top edge of the screen; the liquid passes through the screen and drains away while the solids move down the face of the screen and drop to the collection area. The most attractive features of the stationary screen separator are a lack of moving parts, low maintenance, and no power requirements (Zhang and Westerman, 1997).

<u>Vibrating and rotating screen separators</u> use a continuous motion to aid the movement of the separated solids across the screen and reduce clogging of the screen. Manure is pumped into the center of the screen at a controlled rate and

the separated solids remaining on the screen are slowly discharged at the periphery. Liquid passing through the screen is collected in a pan beneath the screen. With a rotating screen separator, manure is deposited to the top of the screen at a controlled rate. The solids retained on the screen are scraped into the collection area and the liquids passing through the screen are collected into a tank (Zhang and Westerman, 1997).

While screening will remove organic compounds and thus reduce the oxygen demand for aerobic systems, it is unlikely that screening alone (with out further treatment of the liquid fraction) will reduce odor releases from the liquid. This is because screening for particles below 0.075 mm diameter is extremely difficult. (Ndegwa, et al., 2000)

<u>Centrifuges</u> use centrifugal forces to cause separation. There are horizontal and vertical types of centrifuges. A horizontal decanter centrifuge uses a closed cylinder with a continuous turning motion. The centrifugal force separates liquids and solids on the wall in two layers. An auger, turning at a higher speed than the cylinder, moves the solids to the conic part of the separator, where they are discharged. The liquid leaves the cylinder at the other end (Zhang and Westerman,1997). Centrifuge-type separators result in more liquid removal and therefore a dryer solids fraction.

<u>Chemical treatment/flocculation</u> of wastewater involves the addition of chemicals to alter the physical state of dissolved and suspended solids to facilitate their removal by one of the separation processes previously described. Two approaches include chemical precipitation (commonly used to remove phosphate from industrial wastewater treatment facilities) and coagulation, which is a process of aggregating suspended (colloidal or dispersed) particles to form flocs through addition of electrolytes or organic polymers.

Zhang and Lei (1998) tested five polymers and two metal salts for their ability to improve the performance of solid/liquid separators. The polymers were tested first, using swine manure with 1% total solids (TS). The best performing polymer, 255G, was then used for further tests to study the polymer dosage requirements for use alone or in combination with a metal salt. Polymers used with 1%TS manure performed very well and yielded 71 to 76% TS removal and 77 to 83% volatile solids (VS) removal from swine manure. As a comparison, without the polymer, the TS and VS removals were only 15% and 17%.

The performance of various mechanical separators is summarized in the table below.

Performance of mechanical separators.[1] (Zhang and Westerman, 1997)

| Separator | Screen Opening, mm | TS in Raw Manure, % | Separation Efficiency[2], % | | | | | TS[3] in Solids, % | Liquid Flow Rate, l/min |
|---|---|---|---|---|---|---|---|---|---|
| | | | TS | VS | COD | TKN | TP | | |
| Stationary Screen | | | | | | | | | |
| | 1.5 | 0.2-0.7 | 9 | - | 24 | - | - | 6 | 235 |
| | 1.0 | 0.2-0.7 | 35 | - | 35 | - | 69 | - | - |
| | 1.0 | 1.0-4.5 | 6-31 | 5-38 | 0-32 | 3-6 | 2-12 | 5 | - |
| Vibrating Screen | | | | | | | | | |
| | 1.7 | 1.5 | 3 | - | 6 | - | - | 17 | 37-103 |
| | 0.841 | 1.5-2.9 | 10 | - | 1-14 | - | - | 18-19 | 15-103 |
| | 0.516 | 1.8 | 27 | - | 24 | - | - | 20 | 37-57 |
| | 0.516 | 3.6 | 21-52 | 25-55 | 17-49 | 5-32 | 17-34 | 9-17 | 38-150 |
| | 0.39 | 0.2-1.7 | 22 | 28 | 16 | - | - | 16 | 67 |
| | 0.44 | 1-4.5 | 15-25 | 18-38 | 13-26 | 2-5 | 1-15 | 13 | - |
| | 0.104 | 3.6 | 50-67 | 54-70 | 48-49 | 33-51 | 34-59 | 2-8 | 38-150 |
| Rotating Screen | | | | | | | | | |
| | 0.75 | 2.5-4.12 | 4-8 | | 4 | | | 16-17 | 80-307 |
| | 0.8 | 1-4.5 | 5-24 | 9-31 | 2-19 | 5-11 | 3-9 | 12 | - |
| Belt Press | | | | | | | | | |
| | 0.1 | 3-8 | 47-59 | - | 39-40 | 32-35 | 18-21 | 14-18 | |
| Centrifuge | | | | | | | | | |
| | - | 1-7.5 | 15-61 | 18-65 | 7.8-44 | 3.4-32 | 58-68 | 16-27 | - |

Solid/liquid separation, like other operations on animal farms, requires initial capital investment for the separator system and installation, labor for the system's operation, maintenance and repair. The retail price of mechanical separators varies from \$10,000 to 50,000+, depending on the type of separator and its capacity. The throughput capacity of a typical mechanical separator varies from 100 to 600 gal/min. A typical finishing facility with a flush system will require a minimum of 15 gal of wastewater per finishing pig per day. The flow rate that a separator must be capable of handling for a given number of pigs depends upon the rate of flow through the flush system and whether or not there is a means for holding the fresh wastes prior to entering the solid/liquid separator. Separator with a throughput capacity of 600 gal/min can accommodate at least 6,000 finishing pigs.

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[1] This performance data should only be used as reference data when evaluating different types of separators. The testing and reporting procedures used by different researchers varied greatly, as did the manure used for testing. Field tests are always recommended for obtaining accurate information abour a particular separator for a specific application.

[2] TS= Total Solids; VS = volatile solids; COD = chemical oxygen demand; TKN = total kjeldahl nitrogen; TP = total phosphorus

[3] Refers to the % solids in the separated solids. One minus this number is the % moisture, wet basis

For the same capacity, screens are less expensive than presses or centrifuges (Zhang and Westerman, 1997). The same researchers found that the economics of using solid-liquid separation on animal farms is determined by the amount of manure to be processed, the extent of solids removal from the manure, and the potential for solids reuse and value recovery.

## Summary

Separating solids from the waste stream can reduce the odor potential of the resulting liquid, if the separation effectively removes small particles. It is critical that the solids be handled appropriately, or a new odor source may be introduced. Solids separation may be one step in a waste treatment process. For example, it can reduce organic loading on an over-loaded lagoon, thus reducing the odor emissions from the lagoon. The degree of odor reduction will depend upon the performance of the separator and the handling of the resulting solids. Solids separation is most likely to be cost effective in large operations that implement waste treatment options such as aeration.

## Technologies Designed to Treat Waste and/or Reduce Odors from Waste Storage

Waste treatment technologies are generally classified as aerobic (in the presence of oxygen) or anaerobic (without oxygen). Mixed systems, which employ both aerobic and anaerobic strategies during various phases of treatment, are also possible. Most lagoons, pits and other facilities for handling swine wastes that are currently employed are anaerobic; submerged materials in these systems are not exposed to air and the decomposition that occurs is accomplished by anaerobic microorganisms.

**Anaerobic Lagoons.** In virtually all confined animal feeding operations in Virginia, waste is collected and stored, and then land applied according to a nutrient management plan. Most swine operations in Virginia employ an anaerobic lagoon to both treat and store the waste. The lagoon is sized to include a minimum treatment volume, a sludge storage volume (sludge is the non-biodegradable portion of the waste), and temporary storage of rain and wastewater. The storage volume required is based upon a volatile solids loading rate, which is a function of the climate where the lagoon is located (the warmer the climate, the greater the loading rate.) An additional one-foot of freeboard (height between the top of the berm and the waste level in the lagoon) is also included in the design volume. Effluent from the lagoon is typically circulated back into the production facility to flush wastes from the building to the lagoon. A properly functioning lagoon will accomplish up to a 90% reduction in biological oxygen demand. Lagoons can be designed with one or two holding cells. A two-cell lagoon allows the treatment volume to remain constant, which provides more effective treatment.

Anaerobic lagoons rely on bacteria to decompose wastes. These bacteria can process wastes, with minimal odor emissions. However, if the waste loading rate is too great, or the bacterial population is shocked with batch loadings (as opposed to continuous or reasonably continuous loadings), problems can arise. All bacterial activity is temperature dependent, and the activity within a lagoon slows significantly in the winter. In the spring, there is generally an excess of organic matter present that accumulated over the winter; the combination of warming temperatures and excess organic matter results in increased bacterial activity. Very vigorous activity is often observed on the lagoon surface and greater amounts of biogas and odorous compounds are produced. This typically is referred to as lagoon turnover (Lin et al., 2000).

**Biogas Production.** While methane is naturally produced by bacteria in livestock manure, technologies can be implemented to optimize methane production and capture the gas so that it may be utilized. In certain circumstances, the methane gas can be economically captured and used on-farm to offset commercial energy expenditures. In these cases, the farm operation can both increase revenues and reduce odor emissions by implementing an anaerobic digester.

AgSTAR, a cooperative venture sponsored by USDA, EPA, and the DOE, encourages the use of methane recovery technologies at confined animal waste feeding operations where such use is economically justified. AgStar describes two types of anaerobic digesters that are typically used to recover methane on swine farms. They are covered lagoons and complete mix digesters. These systems are often called digesters because they finish digesting the proteins, carbohydrates, and fats left in animal wastes. During this digestion process, methane gas is produced as a by-product. A gas-tight cover over the digester captures the methane, which may be converted into electricity or used to fuel gas-fired equipment.

<u>A covered lagoon digester</u> consists of a two-stage lagoon, where the first stage is covered and serves as the digester. Manure is pumped into the first stage, which is a constant-volume-covered lagoon digester, where the undigested solids are broken down by bacteria. The gas is then captured under the cover and transported to where it may be utilized as an on-farm energy resource. The biologically stabilized nutrient-rich effluent is pumped (or allowed to flow by gravity) to the second stage lagoon, which acts as a storage pond until the effluent is land applied. Where a single stage lagoon currently exists, it may be possible to build a new cell to act as the digester and employ the existing lagoon as the second-stage or storage pond.

Covered lagoon digesters work best in temperate and warm climates where the manure is handled as a liquid with a solids concentration of less than 2%. These systems are attractive to most livestock facilities as they are often economical and practical in design. The climate in Virginia will allow for seasonal collection of biogas for energy production. However, it is likely to be too cold to produce energy during the coldest months. During this time, the biogas produced could be flared off. (AgStar Handbook, http://www.epa.gov/agstar/library/handbook.html)

A complete mix digester, unlike a covered lagoon digester, is heated and mechanically mixed to provide a homogenous manure substrate. Manure is pre-treated in a mix tank where additional water or manure solids are added to obtain the optimal solids concentration. As in the covered lagoon, methane gas is produced in the complete mix digester, trapped under a gas-tight cover, and transported to gas utilization equipment. Treated manure is pumped from the digester to a storage pond where it is stored until field application. Complete mix digesters may be used to treat manure from swine farms with scraped systems. These systems may operate in any climate as supplemental heat, generally recovered from the engine generator, is used to obtain the optimal methane production temperature. These systems typically handle manure slurries with a solids concentration between 3 and 8%.

Summary

Anaerobic lagoons are widely used to treat animal wastes. In warm climates, if they are properly designed and operated, they can successfully treat manures to significantly reduce the biological oxygen demand and reduce nitrogen and phosphorus content of the effluent. Nutrients will be stored in the sludge layer within the lagoon. Odor emissions will be greatest during spring, when biological activity begins to rise with increasing ambient temperatures and there are excessive nutrients present that have accumulated during the cold season. This sudden rise in activity can result is significant odor emissions.

Anaerobic digesters can significantly reduce odor emissions, and in some cases may be less costly than a lagoon system. Digesters are most likely to be cost effective in larger operations where there is sufficient on-farm energy demand to use the biogas produced.

**Aerated Systems.** In contrast to the anaerobic processes, aerobic systems have some level of free oxygen present. When present, free oxygen enables aerobic bacteria to decompose the organic compounds in waste more extensively than anaerobic bacteria do. The end products of this breakdown are typically water, carbon dioxide, and other simple molecules. In this reaction, many of the organic compounds related to offensive odors are minimized.

The value of aeration in reducing offensive odors has been demonstrated by many researchers using olfactometric methods (Williams et al., 1989; Williams, 1984; Pain et al., 1990.) They found that odor emissions following land spreading were reduced by 50-80% if the slurry was aerated prior to application.

There are various types of mechanical aerators available. Crumbly (1987) classified aerators into five types and provided an average range of efficiencies for each type. This information is provided below:

Types of aerators and range of aeration efficiencies from various studies as reported by Cumby (1987).

| Type of Aerator | Aeration Efficiency Range (lb $O_2$/kW-h) |
|---|---|
| Compressed air | 3.3-10.6 |
| Mechanical surface | 2.2-4.4 |
| Mechanical subsurface | 2.2-4.4 |
| Combined compressed air/mechanical | 4.4-6.4 |
| Pumped liquid | 1.5-3.8 |

Westerman and Zhang (1997) caution that actual aeration efficiency is dependent upon manure characteristics and vessel size. Therefore, the efficiencies of particular aerators should be determined under conditions as similar as possible to the actual aeration setup. Operating costs are largely dependent upon aeration efficiency.

There are various strategies for aerated manure treatment including batch or continuous, operation at various temperatures, high or low aeration rates, suspending the microbial population in the waste or attaching it to a fixed film over which waste is directed. The type of treatment that is desired drives the selection of a treatment strategy.

**Batch processes** involve placing a given volume of waste in the system, treating that waste, and removing that same quantity as one unit. While this simplifies operation of the treatment process, drawbacks include—unsteady microbial population, oxygen demand and heat output and an inconsistent treatment. The period of high activity at the beginning of batch aeration can lead to major foaming problems. Batch treatment is the most effective way to reduce pathogens.

**Semi-continuous processes** occur when waste is added and removed during the treatment process (rather than an all-in/all-out or batch treatment strategy.) This tends to be the result of the natural operation of a farm. Semi-continuous loading supports a steadier microbial population. The general principle is a repeated cycle of operations including aeration, settling, pumping out and filling. It usually requires a mean treatment time of several days.

**Continuous processes** involve the continuous flow of untreated manure into the system and the flow of treated manure out of the system to maintain steady operating conditions. In this system the level of nutrients in the aeration vessel will be relatively low and this will limit microbial activity.

**Activated sludge process** consists of two stages—the first provides aeration of the wastewater and the second removes suspended solids by sedimentation. Typically, some of the sludge from the second stage is recycled back into the aeration vessel to maintain a high level of microbial activity. This is the process most commonly used at municipal treatment plants.

Typically, aerated systems are classified as aerobic or facultative. If the dissolved oxygen remains present throughout the depth of the vessel, the system is considered to be an aerobic design. Systems such as this are typically found in municipal and industrial treatment operations. However, these systems have not been utilized by agriculture for several reasons. First, municipal and industrial operations have trained, full time staff to ensure the systems are operating properly. Farmers often do not have the time required to monitor and adjust these systems. Furthermore, the amount of energy input required to oxygenate the entire waste volume is typically prohibitive considering the small profit margins farmers operate under. Westerman and Zhang (1997) determined that $14/yr/finishing pig space would be required to completely stabilize the waste with continuous aeration. In order to make things economically achievable, often oxygen is supplied to1/3 to ½ the BOD loading. This reduces the release of odorous compounds, often to acceptable levels.

Facultative aerated lagoons may have more promise to the agricultural community. A facultative lagoon is stratified into an upper layer that has dissolved oxygen (free oxygen) present, and a lower layer that is anaerobic. Since only a portion of the total waste volume is being aerated, the energy required to operate the system is greatly reduced while odor control is maintained. Typically aeration of the surface to a depth of 0.5 to 2 feet is recommended, with lagoons being a minimum of 10 feet in depth (Barker et al., 1980; Schulz and Barnes, 1990; Zhang et al., 1996).

While agriculture has primarily used the above systems in association with continuous lagoon treatment, other variations in treatment strategies exist. Many new studies are utilizing processes typically found in municipal wastewater treatment plants. For example, Westerman et al. (1998) examined a process involving a fixed-media biofilter to aerobically treat swine manure. They found significant reductions in odor intensity and irritation. Other treatment strategies such as activated sludge (Goodrich and Petering, 1999) and sequencing batch reactor treatment (Bicudo et al., 1999) have also shown significant reductions in odor emissions.

The level of oxygenation required, and therefore the cost, will depend upon the degree of stabilization and/or odor control required. Burton (1992) notes that the length of time the waste will remain odor free after treatment depends upon the aeration level. Pain et al. (1990) observed an 80% reduction in odor when land-applying slurry that was aerated at a 10% dissolved oxygen saturation level, compared to slurry aerated at a 1% saturation level. Therefore, some farms may be able minimize treatment costs by implementing lower levels of aeration.

<u>Summary</u>

Aeration significantly reduces odors, but requires costly energy inputs. Many aerobic treatment systems involve complicated multi-staged operations, which require trained personnel to operate. However, some aeration of a lagoon may reduce odors at a relatively low cost.

A potential environmental concern from aeration is the release of ammonia. This is especially a problem if excessive flow rates are used. Burton (1992) suggests that excessive ammonia releases can be avoided by longer treatment times at lower aeration levels. This allows populations of nitrifying bacteria to develop, which promote the conversion of ammonium to nitrite instead of ammonia.

## Bedded Systems

Most large-scale confined swine feeding operations use liquid manure handling systems. Liquid systems allow for a large degree of automation in the waste handling system. In contrast, bedded systems create solid manure; the animals bed and dung on a deep bedded-pack of cornstalks, straw, or other materials. The structure used for this production model, which has gained some popularity in the high plains, Midwestern United States, and western Canada, is a hoop house. One reason for the popularity of this system is that the initial cost of the structure is significantly less than a typical, environmentally-controlled confinement system (Brumm, et al., 1997).

The bedded pack system represents a paradigm shift from the typical modern confinement building. Using solid manure systems rather than liquid manure systems is generally considered to reduce odor emissions. Although gases and dust are emitted from solid or bedded systems, most people feel that odors from bedded systems are less objectionable than odors from liquid systems.

There are two categories of deep-bedded housing systems—carbon-based and sand-based. The sand-based system relies on removal of liquids through evaporation into the atmosphere, which results in a cooling of the environment. For this reason, sand systems are limited to use in hot regions of the country and will not be discussed further herein.

Carbon-based systems attempt to provide a bedding pack with the proper carbon/nitrogen ratio and physical structure to assure optimal animal environment by absorption, evaporation, and composting. Two management techniques have been tried—the single approach, which involves putting a large volume of bedding material in the facility at the beginning of a growout cycle with no further additions of material, and the continuous addition approach, which starts with less bedding for the initial pack, but involves frequent additions to maintain a proper bedding environment. The single approach has raised concerns for animal welfare, air quality within the building and the potential for environmental pollution. The continuous approach provides more control of building environment, but represents a greater labor input.

Within a deep-pack structure, the animals tend to define distinct bedding and dunging areas. The selection of these areas varies from group to group and season to season.  During cold weather, animals tend to bed on the south end of the house (where it is warmest) and dung at the north end and along the east and west walls.  Under warm conditions, they often dung in the middle of the house and sleep near the walls where it is coolest.  One implication of the distinct bedding/dunging areas is that the nutrient content of the solid material that is removed from the house is highly variable.  This makes land application under a nutrient management plan difficult; some areas may receive too much nutrient loading, while others may suffer nitrogen immobilization and crop stress due to the addition of a high carbon source without adequate nitrogen.

Richard and Smits (1998) conducted a six-week comparative composting trial using a deep-pack from a swine grow-out in a hoop house.  Two methods of windrow construction and two strategies of compost turning were investigated—one using a tractor-loader bucket and another using a stationary manure spreader to unload the manure into a pile.  Each of these windrows was divided into two sections, one of which was turned every time the temperature exceeded 149 F and the other, which was not turned during the six-week trial.  They estimated nitrogen losses and volume reduction for each treatment.  All four treatments achieved thermophilic temperatures within the first week, indicating the relative ease with which the deep pack manure can be composted.  Mass reduction over the six weeks ranged from 63% for the manure-spreader-built-and-turned piles to 16% for the loader-built-and-unturned piles.  This reduction is significant, since it will reduce the number of trips required for land application.

Richards and Smits (1998) also estimated the nitrogen losses that occurred in the hoop system by estimating the nitrogen inputs from the pigs and calculating the nitrogen content of the deep pack at cleanout and after composting by analyzing for nitrogen content and multiplying the average nitrogen concentration by the mass of the bedded pack or compost section.  The results of their analysis indicate that approximately 30% of the nitrogen is lost while the pigs are still in the hoop.  Presumably this loss is in the form of ammonia volatilization, but a portion could also be lost through leaching to the soil.  An additional 10% of the nitrogen was lost during cleanout, presumably due to volatilization as the bedded pack was broken apart.  The composting strategies that resulted in the greatest volume reduction also resulted in the greatest nitrogen reduction—60% cumulative loss was observed in the manure spreader built sections.  Richards and Smits comment that these losses are greater than reported by USDA (1992) for other manure management systems and warrant further study.

The table below (Brumm et al., 1997) presents estimated bedding requirements for deep-bedded systems in the Midwest.  Bedding requirements are approximately 30% greater during cold weather, when it is critical that the environment remain dry for animal warmth.  Bedding requirements in Virginia might be slightly lower, since winters are not as long or as severe as in the Midwest.

**Estimated Amount of Bedding Need for Grow-out of Pigs in a Hoop Structure (Brumm et al.,1997)**

| Material Used | Avg. Amount of Yearly Bedding lbs/pig | Amount of Summer Bedding lbs/pig | Amount of Winter Bedding lbs/pig |
|---|---|---|---|
| Shredded corn stalks | 200 | 125-150 | 200-250 |
| Corn cobs | 240 | 150-180 | 240-300 |
| Barley Straw (long) | 240 | 150-180 | 240-300 |
| Oat Straw (long) | 180 | 110-135 | 180-225 |
| Wheat Straw (long) | 225 | 140-170 | 225-285 |
| Sawdust (hardwood) | 335 | 210-250 | 335-415 |
| Sawdust (pine) | 200 | 125-150 | 200-250 |
| Wood shavings (hardwood) | 335 | 210-250 | 335-415 |
| Wood shavings (pine) | 250 | 155-190 | 250-315 |

Hill (2000) argues that proper bedding selection and management are crucial to the successful operation of a deep-pack bedding system. He provides a table listing possible organic bedding materials along with a list of concerns for each material. According to Hill, wheat straw is the industry standard. Oat straw can cause skin rashes, soybean stubble/straw can cause puncture wounds to small pigs, grass straw and corn stalks can be dusty and moldy, ground corn cobs and recycled paper can cause dust problems, whole corn cobs can cause leg injuries, rice hulls are dusty and compact too much.

Hill (2000) reports an analysis of multiple year production results of a large contract swine producer with many deep bed swine production units. The buildings were all naturally ventilated and continuously bedded using cornstalk, soybean stubble, and straw as bedding sources. The goal was to maintain a minimum 14 inches of pack depth with a 60% lying area along the centerline of the houses and a limited dunging pattern along the sidewall. Detailed data were collected concerning the type of bedding material, depth of bedding, and whether or not the desired dunging pattern was established. Performance results were compared for sites that met the goals for bedding management and those that did not. Sites meeting the goals had better average daily gain, required less feed per unit weight gain, showed greater daily feed intake, had a higher livability percentage and a lower cull percentage than the sites that did not meet the bedding goals. The majority of the increase in mortalities due to poor bedding management were associated with increased disease challenges and stress-related deaths, suggesting a decrease in animal welfare for poorly bedded facilities.

Brumm et al. (1997) report that pigs raised in hoop structures have poorer feed conversion efficiencies, requiring approximately 0.3 more lbs of feed per pound of gain than swine raised in a confinement system during winter conditions. During summer conditions, approximately 0.1 lbs more feed per pound of gain is required in hoop houses. However, in both winter and summer, the rate of gain was as good, if not slightly better, in the hoop house.

Brumm et al. (1997) report that the health of pigs in hoop structures appears to be very good and that death loss has been minimal in hoop structures and is often lower than in confinement buildings. They also report that respiratory problems have been minimal. There is concern that pathogens could build up in the dirt floor under the bedded pack with long term use. Roundworms can be an additional long-term health management concern if the pigs are not wormed or parasite free before entering the facility.

Brumm et al. (1977) presents a cost comparison for hoop houses versus confinement housing for grow-finish swine production. They estimate a $0.38 savings per hundredweight produced in the hoop house model. However, the economics depend upon a reliable and affordable source of quality bedding material.

Summary

The deep-pack system shows advantages for odor control, pig health, and production. However, the systems are labor intensive, and highly dependent upon a reliable and affordable source of bedding material. If crop residue is removed for use as a bedding material (rather than being left in the field), this may have a negative environmental impact in areas with highly erodible land. Also, some environmentally-responsible method for storage of the solid manure will be required if cleanout occurs during the winter season. Finally, the durability of the hoop structure and covering materials has not been fully proven.

<u>Summary of Odor-Reducing Technologies Reviewed</u>

Odor emissions from agricultural facilities are receiving a great deal of attention from government regulators, facility owners and the general public. Some technologies are available for reducing odor emissions, but all have associated costs, and few show economic benefits for the producer (beyond avoiding costly litigation or the prospect of being shut down.) The following table summarizes some of the technologies that have been proposed and tested.

**Summary of Odor-Reducing Treatment Options**

| Process/System | | Description | Advantages | Disadvantages | Cost[1] |
|---|---|---|---|---|---|
| **DUST REDUCTION** | **Washing Walls** | A wetted pad evaporative cooling system is installed in a stud wall about 1.5m upwind of ventilation fans and downwind of hogs in a tunnel-ventilated building. | There is a 50% reduction of dust and 33% of ammonia when the ventilation rate is low. | Because of low residence time, odor removal is not effective at high ventilation rates (summer conditions.) | $5.70 per pig space Instal-lation cost |
| | **Oil Sprinkling** | Vegetable oil sprinkled daily at low levels in the animal facility | Effectively reduces dust and odor levels. | Sprinkling oil forms greasy residue on the floor and pen partitions, which increases labor required for cleaning | $2.50 per pig space instal-lation cost;<br><br>Oil costs not reported. |
| | **Windbreak Walls** | Many odorous compounds are absorbed on dust particles. A wall made a tarp or other porous material placed 3-6 m from exhaust fans. | May reduce odor and dust emissions | Periodic cleaning of dust on walls is necessary for sustained odor control | $1.50 per pig space install-ation cost<br><br>Some cleaning cost expected. |

[1]Cost estimates as presented by university or private industry sources. Cost estimate methodology may vary widely across sources, and comparisons between technologies should be exercised with caution.

**Summary of Odor-reducing Treatment Options (Continued)**

| Process/System | | Description | Advantages | Disadvantages | Cost[1] |
|---|---|---|---|---|---|
| **AIR TREATMENT** | **Biofilters** | Odorous gases are passed through a bed of compost and wood chips; bacterial and fungal activity help oxidize volatile organic compounds. | Effectively reduces odors and hydrogen sulfide emissions. | Requires replacing existing ventilation fans to accommodate increased pressure drop through filter. | $1.00-1.50/1000 cfm installation cost. $3/1000 cfm maintenance cost.. |
| | **Ozonation** | Powerful oxidizing agent, which is injected into the air in the production facility. | May have positive health effective. | Effectiveness currently unproven. | $10 per pig space (finishing) installation cost. $0.45/head annual operating cost. |
| M**ANURE COVERS** | **Straw** | Straw is blown over the surface of the manure storage. | Odor reduction. | Temporary solution; straw sinks after a certain period. | $0.10/sq ft |
| | **Plastic Cover** | Several varieties of plastic can be placed over manure storage. | Helps reduce odor and hydrogen sulfide emissions. | Significant capital cost. | $1.00/sq ft |
| | **Clay balls/ Leka rock** | Floating clay balls, which are placed over manure. | Helps reduce odor and hydrogen sulfide emissions. | Care must be taken during agitation and pumping; significant capital cost. | $2-5/sq ft for 6 inch thickness installation cost. May need additional material every few years. |

[1]Cost estimates as presented by university or private industry sources. Cost estimate methodology may vary widely across sources, and comparisons between technologies should be exercised with caution.

## Summary of Odor-reducing Treatment Options (Continued)

| Process/System | | Description | Advantages | Disadvantages | Cost[1] |
|---|---|---|---|---|---|
| MANURE TREATMENT | **Bedding** | Dry carbon source added to animal pens to promote comfort and soak up manure. | Significant odor reduction; partial composting of bedding in place. | Must harvest or buy bedding and add it throughout the year; increased volume of manure to haul. | $0.38 per hundred weight produced. Highly dependent on source of bedding. |
| | **Manure Additives** | Chemical or biological products are added to the manure. | May reduce odor and ammonia emissions. | Odor reduction questionable; may not achieve desirable results under field conditions. | $0.25 - $1.00 per pig (or more) |
| | **Solid/liquid separation** | Separation of solid and liquid fraction to remove a fraction of the odor-causing compounds from liquid waste stream. | Can reduce odor in liquid manure storage pits. Removing particles smaller than 0.25mm is suggested. | Significant operational and capital costs. Requires management of the solid waste fraction that is generated. | $1.00 - $3.00/pig marketed |
| | **Composting** | Biological process where aerobic bacterial convert organic material into a stable, odor-free material. | Reduces organic matter as well as odor. | Significant capital and operating costs. | $0.2 - $0.4/pig marketed |
| | **Aerobic treatment** | Biological process where organic matter is oxidized by aerobic bacteria. | Effectively reduces odor, nutrients and organic matter. | Significant capital and operating costs. | Highly variable – depends on system |
| | **Anaerobic treatment lagoon** | Biological process where organic carbon is converted to methane by anaerobic bacteria. | Reduces nutrients and odor. | Can cause odor releases when weather changes – spring/fall. | _______ |
| | **Biogas Production** | Implemented to optimize methane production and capture the gas so that it may be utilized. | Effectively reduces odor emissions. | High capital costs; significant maintenance required. | _______ |

[1] Cost estimates as presented by university or private industry sources. Cost estimate methodology may vary widely across sources, and comparisons between technologies should be exercised with caution.

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