Odour and Air Quality

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Science to
Social Issues

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1.1 Introduction

Intensive livestock production can result in odour problems for the neighbouring population. Areas of intensive livestock production will expand, develop and exist where feed is grown, water is available and transportation costs are reasonable. Odour nuisance can be assessed by considering the frequency, intensity, duration and offensiveness of the manure odours (FIDO). The integrated FIDO effect relates to the incidence of annoyance and nuisance. Since the nose is the sensor used to evaluate odour annoyance, odour nuisance can be very subjective. Odour responses differ in everyday life and in an odour measurement lab. In the real world the whole body is exposed (sight, hearing, smell) whereas in the lab only the nose is involved. Social interactions also affect the odour response.

1.2 Olfactory System

The olfactory bulb is wired into the brain similarly to that of the retina. No synapses occur, no integration of input signals occurs, and the nerves regenerate themselves. During sniffing, air is drawn across the entire turbinate area in the nose. Both inhaling and exhaling are used to evaluate odours. The olfactory bulb output is integrated with emotions and memory.

1.3 How Odours Are Generated

Odours are generated from the decomposition of the feces and urine. Over 160 compounds have been identified in odours from swine operations (O'Neil and Phillips 1992). The principal constituents are ammonia, amines, sulphur-containing compounds, volatile fatty acids, indoles, skatoles, phenols, alcohols and carbonyls (Curtis 1993). Some of the gases are produced as manure undergoes anaerobic degradation, which occurs in the absence of oxygen. Since anaerobic degradation normally occurs at manure storage temperatures lower than 20°C, the rate of methane production is low, thus products from the acid-forming bacteria predominate. These by-products are very odorous.

1.4 Sources of Odours

Typical sources of odorous gases on pig production sites are the barns, manure storages and when manure is spread on land. Odours in barns are thought to be primarily ammonia-based since much of the fecal material and urine undergoes a drying process while stored temporarily on a solid floor or a slatted-floor surface. However, once the fecal material and urine drops into a liquid storage, the ammonia is immobilized as ammonium hydroxide in solution.

The majority of the odours in barns are thought to be generated from feces or urine deposited on solid surfaces. High odour levels in barns are also caused by low ventilation rates, poor air distribution systems or high humidity levels.

In long-term manure storages, sulphur-containing compounds such as hydrogen sulphide tend to predominate since the nitrogenous compounds remain in solution. This suggests that the odours from the buildings differ in character from outside manure storages. Also, odours from manure storages appear more persistent than building odours. This means that storage odours have a longer hang time since their intensity persists over a longer distance as they are diluted.

1.5 Odour and People

People are becoming increasingly intolerant of malodours generated by livestock operations. However, to date, there exist little data of what levels of odours are acceptable to the public in terms of frequency, intensity, duration and offensiveness. Therefore, it is difficult to determine what types of odour control are necessary or estimating the magnitude of costs (Flesh et al. 1974).

An attitude survey is one way of evaluating community problems caused by manure odours. Odour evaluations are very personal, thus expressions of annoyance leading to intolerance may be anticipated (Flesh et al. 1974). Also, odours are experienced in everyday life situations. These exposures normally take place not when our main focus is on an evaluation of the air around us, but when we are engaged in work, social interactions and other distractions. Another way of evaluating community problems due to manure odours is to sample the odours, and take the samples to a laboratory, where an experimental participant produces a “yes” or “no” as to whether or not they detect the odour (Walker 2001). In addition to smelling the odour, the person experiencing the odour may have a visual image of the source, a headache, irritation of the eyes, nose and throat, exacerbation of asthma and memory of past odour experiences. As Walker (2001) points out, "odour impact" includes numerous perceptual and physiological effects of short-term chemical exposures.

It is difficult to quantify the effects odours have on people. This is because quite often humans respond differently to odours. A neutral odour to one may be nauseating to another. Some odours are non-offensive when weak and offensive when strong, depending on the person's sensitivity. An odour may possess one quality when first smelled and another when smelled over time.

Sensitivity to odours changes with time of exposure. We either adapt or become sensitized. Adaptation is a reduction of responsiveness such as fatigue (Wachs et al. 1989). During long-term adaptation, a more persistent reduction in response occurs perhaps in hours or days. People who work in odorous environments usually experience this. Sensitivity may increase as a repeated, intermittent, sub-threshold stimulus induces an amplification of nerve responses such that a person may become super-sensitized to an odour stimulus. Past experiences and relationships to some odours can change sensitivity and attitudes to specific odours (Frey 1995). Thus, an odour that is initially pleasant can become a nuisance as a result of an excessive FIDO factor.

1.6 Manure Treatment/Storage

Manure treatment and storage type influence the character of the odour. Anaerobic storage appears to retain many of the odours in solution. Only when disturbed, do gases escape from the liquid. Emptying or filling can become very odorous events. Storages with a buildup of solids are often odorous since large, solid materials float to the top when they become buoyant from the gases attaching to them. Aerated manure systems often generate large amounts of ammonia when the C:N ratio is low or the oxygen levels or detention times are too low. Also, some odorous compounds such as methylamine or mercaptans become more odorous when oxidized to chloro-amine and dimethyl disulphide, respectively (McGinley 2001).

1.7 Odour Perception and Measurement

Sensory responses follow a "power law" referred to as Steven's Law, where the odour strength increases as a power function of the concentration of the odour stimulus (McGinley et al. 2000).

$$I = kC^n$$

where: I = odour intensity (strength),
C = mass concentration of odourant, and
k, n = constants for every odourant.

This equation is a straight line on a log-log plot.

Odours can be evaluated in several ways. Odour samples can be brought to an olfactometer laboratory to measure concentration (threshold), persistence and hedonic tone. Odour samples are normally collected in 10L Tedlar bags. A vacuum case with vacuum pump is used to draw the sample from the source. Odour testing normally occurs within 24 hours after the samples are obtained. The odour laboratory is an odour-free, non-stimulating space. A comfortable waiting room is available for laboratories with a single panelist olfactometer, whereas all the panelists are seated around an 8-panelist olfactometer (Feddes et al. 2001).

Odour panels consist of individuals who are selected and trained following the European standards (CEN 1999). Normally, approximately 30% of the population is eligible to be a panelist. Qu et al. (2001) developed a normalization algorithm to normalize the olfactory response of an odour panel. When following the European standard, panelists must be able to detect n-butanol (a reference odour) between concentrations of 20 and 80 ppb (geometric mean of 40 ppb). Qu et al. (2001) found that panelists who detected n-butanol outside this range achieved the same results when their responses to environmental odours were normalized. The normalization equation is as follows:

$$\mu_{env} = X_{env} (X_{nbut} / \mu_{nbut})^{-0.65}$$

where: X_{env}, X_{nbut} = the detection threshold for the unknown odour and the reference n-butanol measured by the non-trained panel, and

μ_{env}, μ_{nbut} = the detection threshold for the unknown odour and the reference n-butanol measured by the trained panel.

1.8 Odour Concentration

The olfactometer is used to determine odour threshold concentrations by diluting the odorous air samples with clean non-odorous air. This mixture is presented to the panelists. Initially, the diluted samples cannot be detected by the panelist. As the concentration of the mixture is increased by a factor of 2, it is presented to the panelists. Once it is detected by the panelists, the dilution ratio of the sample and clean air volume becomes the odour unit (OU).

Each panelist must correctly detect the odour at two consecutive dilution ratios. Since the dilution scale is non linear, the geometric mean of the first correct and the previous non-correct dilution ratio is calculated. With this procedure, all the panelist thresholds are averaged to determine the overall detection threshold for which 50% of the individuals will observe the presence of odour (McGinley et al. 2000).

According the European standard (CEN 1999), if the panelists are qualified and meet the standard, the odour unit can be expressed as OU/m^3. Consequently, emission rates can be expressed as OU/s or OU/s per m^2 of surface area. Olfactometer labs around the world use either the European Standards (CEN 1999) or the Australian standards (Heeres and Harssema 1996). These standards are very compatible.

1.9 Odour Pleasantness

The pleasantness of an odour is referred to as hedonic tone. Normally, it is represented on a 21-point scale with most unpleasant represented by a –10, fresh air by 0 and most pleasant air as +10. In some olfactometer laboratories, non-diluted manure odours are presented to panellists, whereas in other laboratories, panelists are presented with diluted odours to evaluate hedonic tone. This measurement is quite subjective, since panelists use their personal experience and memories of odours as a reference scale to make judgment, which they express by adjusting the scale. With non-diluted samples panelists can temporarily lose their sense of smell, while diluted samples may be more representative of the neighbours' responses.

1.10 Odour Persistency

This term describes the rate that an odour's perceived intensity decreases as the odour is diluted (McGinley et al. 2000). Sulphur-containing compounds appear to have a more persistent odour than nitrogen-containing compounds. In other words, a building odour and a manure storage odour with the same intensity will become non-detectable at different distances downstream from the source assuming similar atmospheric conditions.

The persistency of an odour can be represented as a "dose-response" function:

$$\text{Log } I = n \log C + \log k$$

where: I = intensity,
C = concentration, and
n, k = constants for odour.

Intensity of an odour is measured at various dilutions. Constant "k" is the intensity at 0 dilutions or the non-diluted odour, and "n" is the slope. The manure storage odours appear to have a higher "n" value than the building odours.

1.11 Odour Intensity

A method for measuring odour intensity on-site is described by St. Croix Sensory (2000). This method uses trained odour sniffers who are physically brought to the site. The odour sniffers train their noses to assess an odour level instantaneously using a numerical scale 0 to 5 or 0 to 8. Each numerical scale represents an n-butanol intensity (ASTM Standard, E:544-75 1999).

A 5-point scale ranges from 1–25 ppm to 5–2025 ppm n-butanol. The odour sniffers match the intensity of the sample to a series of n-butanol intensities. This method appears to provide greater sensitivity to odours at the lower end of the threshold scale than that possible with olfactometry (Jacobson and Guo 2000). They suggested a relationship between odour intensity and odour threshold as follows:

$$Y = 0.0139\, X^{1.2591}$$

where: Y = odour threshold (odour units), and
X = intensity (n-butanol equivalent, ppm).

1.12 Odour Character

Odours are characterized using a referencing vocabulary for taste, sensation and odour descriptors (McGinley et al. 2000). These odour descriptor categories are illustrated by an odour wheel. The eight categories describe odour as vegetable, fruity, floral, medicinal, chemical, fishy, offensive and earthy. Each category has specific descriptors. By referencing standard designated categories, objective choices can be made for each odour.

1.13 Electronic Nose Technology

The electronic nose is becoming a candidate for measuring odour concentration (Qu et al. 2001). Some use an array of sensors to mimic the human olfactory system in the classification, discrimination and recognition of chemical patterns occurring in various kinds of samples (Schiffman et al. 1996).

This sensing technology is based on unique sorption/desorption dynamics between volatile chemical compounds and an array of proprietary conducting polymers. Each polymer in the sensor array exhibits specific changes in electrical resistance upon exposure to different odour molecules. One constituent of the chemical mixture exposed to the array may interact with certain individual sensors, but not with others. This selective interaction produces a pattern of resistance changes exhibiting a 'fingerprint' of an odour. When an odour is comprised of multiple chemicals, the 'fingerprint' is the sum of their combined interactions with all sensors in the array. In addition to odour composition, odour concentrations can generate different responses on an electronic nose (AromaScan 1999). This suggests that an electronic nose may be used to measure odour concentration. If the odour concentration measured with the olfactometry method can be correlated with the response of a sensor array in an electronic nose for the same odour sample, the goal of using an electronic nose to measure odour concentration will be accomplished.

Qu et al. (2001) used the adaptive logic network (ALN) software, a type of artificial neural network, to develop a function to convert the measurements of a commercially available electronic nose into odour concentrations. A data set was developed by evaluating odour samples with both an olfactometer and the electronic nose. The odour concentrations measured with the olfactometer served as observed values, and the responses of a 32-sensor array in the electronic nose, together with the humidity of the odour sample and reference air, served as input variables. By applying a principal component analysis, the number of input variables in the data set was reduced from 34 to 3, which represented 99% of the variance. This data preprocessing procedure is crucial to the success of using the ALN. Well-trained ALNs combined with an electronic nose can measure odour concentrations with about 20% mean error.

1.14 Evaluation of Odour Control Technologies

The biggest obstacle to developing appropriate odour reducing technologies is measuring odour objectively. Odour parameters are odour intensity, odour concentration, hedonic tone, odour persistence, and odour character. Each technology may affect one or more of these parameters. Only odour intensity and odour concentration can be measured with reasonable objectivity. These two parameters are measured using n-butanol gas as a reference, although this compound does not represent agricultural odours well. It is interesting to note that when odour intensity is reduced by 99% (1000 to 10 OU/m^3) the nose only perceives a log change (3 to 1), that is, a 66% change. Very high removal efficiencies must therefore be attained to achieve a substantial change in the perceived odour.

Misselbrook et al. (1993) derived a relationship between odour concentration and odour intensity of hog slurry. This relationship is assumed to be different for each manure source. This relationship, often referred to as "persistence", is an important variable in odour dispersion modelling. Odours with similar intensities but different persistence could have different minimum distance separation (MDS) between livestock facilities and neighbours.

1.15 Concluding Comments

a. The persistence of building and earthen manure storage odours may be different. These different values will impact MDS values.

b. Little data are available on acceptable odour exposure in terms of frequency, intensity and duration.

c. Odour hedonic tone does not have a standard.

d. The reference gas n-butanol used in measuring concentration and intensity does not appear to represent livestock odours.

e. Electronic nose technology appears to be one way of quantifying odour intensity and character. This technology is very mobile, less labour intensive and not dependent on the subjectiveness of the human nose.

f. Odour reduced by control technology will be perceived as less by the nose than the change in measured odour intensity.

2 Safety Considerations and Health Effects of CFO Emissions

Some of the recently developed confined feeding operations (CFOs) have reached a size where the magnitude of their emissions have raised public concern about risks to their health and safety when living near an CFO. The U.S. EPA's draft standard "Emissions From Animal Feeding Operations" (EPA Draft 2001) identifies 8 major emission categories of interest: ammonia (NH_3), nitrous oxide (NO_x), methane (CH_4), carbon dioxide (CO_2), volatile organic compounds, hydrogen sulphide (H_2S) and other reduced sulphur compounds, particulate matter (PM) and odours. A literature review commissioned by Alberta Pork and the Intensive Livestock Working Group entitled "Documented Human Health Effects of Airborne Emissions from Intensive Livestock Operations" (Auvermann and Rogers 2000), in addition to these major emission categories, listed carbon monoxide (CO) and bioaerosols (micro-organisms and related biochemicals) as possible major emissions from CFOs that could be a health and safety concern. Another U.S. publication, National Livestock and Poultry Environmental Stewardship, Lesson 40, "Emissions from Animal Production Systems", (Jacobson et al. 2000) focuses on the gas emission synergistic effect of creating an overall odour emission in addition to dust, pathogen and flies as possible emission materials of CFOs. CFO odour is generally described as 160+ compounds that include volatile organic compounds, ammonia and amines, phenolics/nitrogen heterocylces and sulphur compounds.

Safety considerations and health effects directly related to the airborne emissions previously described have not been identified although quality-of-life impacts have been identified. Since airborne emissions from CFOs are becoming a more prevalent issue to animal agriculture, the emissions may result in a nuisance to the neighbouring population when their quality of life is altered. The frequency, intensity, duration and offensiveness of the exposure may exceed an acceptable threshold level. Some of the neighbouring population may be sensitive to the airborne emissions (gas/particulate/bioaerosol) and develop respiratory problems. Exposures during spring and fall appear to be more tolerable since they are more likely to be related to land spreading operations. The process of returning the manure to the soil appears to be an acceptable or sustainable option rather than other means of disposal. However, Jacobson et al. (2000) cited research in the U.K. that almost 50% of all odour complaints were traced back to land application of manure. If the land application procedure could be more flexible in terms of time of day, time of year, and wind direction and speed, many complaints could be avoided.

Emissions from the production site appear to be more constant and consistent. These sources would primarily be the animal housing facilities and the manure storage facilities. Emissions from confined animal spaces might include respirable dust particulate, pathogens, flies and manure odours. Jacobson et al. (2000) provides an excellent educational module describing the individual emissions from confined animal feeding operations. The survival rates of pathogens during transport from the source to the receptor is not well understood. Their survival rate may increase if they are attached to the dust particles.

Cleave et al. (2001) carried out an intensive study to determine the amount of airborne endotoxin and microbial DNA that was transported downwind from a swine facility. Their results indicated that the concentration of endotoxin and microbial DNA 600 m downwind from the source was statistically the same as the upwind concentration. The monitored pig production site was a 600-sow including farrow to finish and had a minimum distance separation of 600-700 m (Agricultural Operation Practices Act 2001). With the current emphasis on animal health and biosecurity, the pathogen emission rates would be expected to be minimal. Much of the research in exposure to odours, irritants and toxicity has been carried out for the indoor workplace (Society of Toxicology 2001). Once these substances leave the confined workplace and are dispersed vertically and horizontally away from the source, their levels would be expected to be minimal.

Odour generated by a CFO is caused by the presence of many malodorous constituents of manure degradation during storage. The principal compounds responsible for producing odour are hydrogen sulphide, ammonia and a number of volatile organic compounds (acetic, propionic, formic, butyric and valeric acid; indole, skatole, phenols, volatile amines and methyl mercaptan (EPA Draft 2001).

Since odorous compounds result from anaerobic decomposition of organic compounds, the potential of odour is higher from liquid manure storage/collection systems. In CFOs where manure is stored as a dry solid, odour production should be minimal when the manure is left undisturbed. In an EPA draft report (2001), the effect of the manure management system, pH of manure storage, temperature, time in storage and diet/sulphur, nitrogen and carbon content of feedstuff is described.

Auvermann and Rogers (2000) did an extensive review on human health effects of airborne emissions from intensive livestock operations. They noted that the time-averaged ambient concentrations of the single, high profile, discrete pollutants did not exceed exposure thresholds for human health. However, they point out that a mixture of odorant substances, particulate matter and bioaerosols may have health implications.

Thu (2002) provided a review and critical synthesis of research related to public health concerns for neighbours exposed to emissions from large-scale swine production operations. He points out that some CFOs are of such a size that neighbours of these large scale swine CFOs are experiencing similar health problems to people working in swine environments with a higher frequency. Perhaps, there is a maximum size of CFO that emits particulate/biohazards and gases that dilute to an acceptable exposure at a reasonable separation distance.

From the literature sources cited in his paper, it appears that when the odours are diluted/dispersed to an acceptable exposure level, the levels of particulate matter and bioaerosols can be assumed to be below an acceptable threshold limit. The associated risk is assumed to be minimal. There may be situations such as feedlots emitting particulate matter from dry non-odorous surfaces.

From this we can conclude that odour is the governing atmospheric contaminant and that it is a nuisance constituent. When considering wind direction, wind speed, atmospheric stability and the degree of turbulence involved in dispersing the odorous constituents, the neighbour is exposed to an intermittent odour of varying duration. In some European countries, livestock odour exposure occurs at a high frequency and neighbours appear to adapt and consider it tolerable, whereas in the Prairie Provinces, exposure frequency can be low resulting in a low tolerance.

2.1 Concluding Comments

a. At what distance from a confined feeding operation (CFO) does health risk become unreasonable?

b. Does an MDS value ensure that the health risk is acceptable and that the emission is only of nuisance value?

c. The survival rate of pathogens during down-wind transport is not well understood.

3 Minimum Distance Separation Formulae

With only 4% of our population living on livestock operations, odour complaints about barn, manure storage and manure application are escalating. This is mainly a result of increasing size and the concentration of confined feeding operations (Fraser 2001). Separation siting criteria were introduced in 1970 in Ontario with the introduction of the document "A Suggested Code of Practise" published by the Ontario Department of Agriculture and Food (Fraser 2001). This code was quite restrictive since the MDS values were independent of animal units confined.

In 1976, the MDS formulae were established to: a) provide setback distances between new land uses and the CFO, and b) provide setback distances between new/expanding CFOs and existing land uses. The formulae seem to give consistent results that satisfy most CFO owners and rural neighbours. Fraser (2001) notes that MDS (a) was used at least 100,000 times and MDS (b) was used at least 20,000 times. This suggests that MDS has been a successful method to minimize odour complaints realizing that odours will always exist downward from CFOs. Fraser (2001) concluded that the MDS formulae were under review so that they would be easier to use for the growing number of municipal staff and others not familiar with the agricultural industry.

The current Agricultural Operation Practices Act (AOPA) came into effect in January 2002. In this act, the terms animal unit, expansion, affected party, number of animals (that require registration and that require an approval process), and professional engineers verification are introduced. Also, values are applied to technology factors and expansion factors. The MDS is measured from the outside walls of neighbouring residences to the nearest source of the applicant's CFO. The MDS formula consists of four factors namely: odour production, odour objective, dispersion factor and expansion factor. The odour production factor accounts for the potential nuisance value of the species, number of animals and the type of production system. The odour objective factor describes the sensitivity of the neighbouring land uses. The dispersion factor considers topography, climatic influences and screening options. Lastly, the expansion factor modifies the MDS value as a result of increasing the source odour emissions (AOPA 2001).

Research is underway around the world to determine variance to MDS values. Factors that may affect variances are: a) unique topography, b) physical and visual screening, c) microclimate, d) management practices and e) odour control technology. In some agricultural areas that are conducive to livestock production, variances may need to be applied to reduce the MDS value. The variance allowed for each factor requires intensive research to ensure that the MDS formulae are applied in a fair way.

4 Dispersion of Airborne Emissions

Plume dispersion models have been used extensively to predict odour/airborne particulate levels downwind from the source. When considering atmospheric stability, wind direction and speed frequency, the models predict annoyance at a certain intensity over a year in hours. For instance, 99.5% annoyance free would result in 44 hours of exposure to annoying odours. The models attempt to define the dispersion factor at each site. Since the plume has numerous atmospheric contaminants, each odorous constituent may have a different persistence value. As odours are diluted, their intensity may linger, whereas some odours lose their intensity quickly as they are diluted. The models do not differentiate between odour persistence for earthen manure storages, poultry barns, swine barns, and manure treatment technologies that may affect odour character. Odour persistence will affect MDS values if annoyance is less. Also intermittent odour exposure is considered to be a nuisance. The models also need to include duration of odour and time between odour events. At some interval, odours may not be considered to be annoying and therefore the annoyance level is lower.

Jacobson et al. (2001) describe the "Minnesota Odour from Feedlots Setback Estimation Tool." The OFFSET Model estimates setback distances from odour sources for different percentages of time when odours are "annoyance free" (Nangia et al. 2001). Setbacks are estimated to allow odours to disperse so that odours reaching the receptor will be offensive 0.1 to 1% of the time. This would represent 9 to 90 h/yr. Shauberger and Pirenger (2001) stated that in residential areas in Germany, odour exposures can exceed 10 OU/m^3 3% of the time.

Odour concentrations lower than 20 OU/m^3 are very difficult to measure (Luymes 2003). Often the background level in sample bags can reach 25 OU/m^3. Zhang et al. (2002) related odour intensity to odour concentration for the same odour sample. The equations they presented show that direct measurement of odour intensity with odour sniffers becomes difficult at less than 12 OU/m^3.

Preston et al. (2003) reviewed odour criteria applied in various jurisdictions throughout the world. For Category 1 (single residence) the offset standard ranged between 7 and 50 OU/m^3 and Category 4 most sensitive land use 3 and 10 OU/m^3. Preston et al. (2003) suggested a level of 2 OU/m^3 for Category 4. It appears that using a 1% frequency criterion may be fair to both producer and the neighbouring community. Perhaps a level of 10 OU/m^3 and 1% frequency criteria might be appropriate for single residences. When Preston et al. (2003) calibrated different dispersion models with the AOPA MDS tables, they suggested 4.4 and 5.6 OU/m^3 for Category 1 for a beef feedlot and sow-farrow to finish operation, respectively.

4.1 Concluding Comments

Once a dispersion model has been selected for Alberta, fair frequency and odour concentration criteria must be established so that animal production expansion may occur at a low incidence of odour conflict. Perhaps a very simplistic model can be adopted. As Preston et al. (2003) suggest, a more in depth site-specific dispersion modeling study should be conducted if an applicant wishes to use other screening, topography or climatic factors.

5 Facility Design and Management

Since air exhausted from animal confinement facilities contains manure gases, bioaerosols and other airborne particulate, odour is at times associated with potential health effects. Buildings are thought to release a relatively constant amount of odour compared to outdoor manure storage facilities and land application events. There is no standard method of raising animals in confined facilities. Some utilize liquid manure collection systems while others store manure in solid form. Some animals are confined to cages while others are reared on litter or concrete. Some buildings are ventilated by a mechanical ventilation system while many of the dairy and some pig facilities rely on natural ventilation, i.e., wind in the summer and the stack effect in the winter. Providing each animal with fresh air is challenging during cold weather conditions. Supplemental heat must be kept to a minimum due to energy costs, therefore the minimum ventilation rates are designed to maintain an acceptable air quality. Having the air enter the length of the building uniformly during cold weather can be difficult. During warm weather conditions, ventilations rates are approximately 10 times higher than those during cold weather conditions. During warm periods, air speed is critical in the animal microclimate to increase the heat exchange of the animal and move the heat produced away from the animal.

Odour can be controlled to some extent by maintaining clean buildings, storing manure as a solid, keeping animals clean, frequently removing manure from the animal space, minimizing respirable dust concentrations, and reducing slatted floor area since slats can hold a significant amount of manure. This manure dries and moistens over a period of time, therefore releasing a significant amount of odour. There is some anecdotal evidence that manure or feed additives reduce odour formation or mask the odour present. Diet manipulation has potential if some amino acids in the feed are grossly overfed. This may lead to sulphur and nitrogen excess resulting in high ammonia and hydrogen sulphide concentrations (McGinn et al. 2000).

Exhausting air vertically from a building appears to increase odour dispersion at the source. The difference in dispersion of vertically or horizontally directed exhaust air is not clear. Also the dispersion of low versus high ventilation rates requires investigation. There is some interest in mounting booster fans above the vertical exhaust ducts to project the exhaust air further into the atmosphere to facilitate dispersion. Also, there is little documentation to show if the odour emission rates during winter are different from those during the summer considering the low ventilation rates and higher odour concentration during the winter and the higher ventilation rates and lower odour concentration during the summer.

5.1 Poultry

Many of the modern layer facilities use shallow gutter or manure belts for collecting the manure in a solid form. Broilers, broiler breeders, and turkeys use litter systems. Odours from these facilities are considered to be less offensive than those produced by liquid collection systems. Poultry manure must be kept at a low moisture content. If water spillage from drinkers occurs, odour production escalates dramatically due to increased anaerobic decomposition.

Some chemical additives have been added to poultry litter to lower odour emission rates. However, if poultry litter is maintained in a dry condition, odour problems will be minimal. In the Prairie Provinces, wet litter conditions occur when moisture removal from the animal space by the ventilation air is inadequate and heating systems are under-utilized.

5.2 Dairy

Dairy facilities are either mechanically or naturally ventilated. The majority of the dairy facilities are free stall systems where dairy animals have free access to feed and water. Dunging occurs in the alleyways. Little information is available to indicate how frequency of cleaning solid floored alleyways compares to slotted floor alleyways where the manure is stored beneath floor level. Odours are usually not a problem if animals are kept clean and the manure is removed on a daily basis. Spoiled feed and manure in inaccessible locations must be avoided.

5.3 Swine

Swine barns are usually considered to be more odorous than other animal production facilities.

5.3.1 Gestation and breeding

Swine gestation and breeding facilities range from pasture systems with limited shelter to environmentally controlled facilities with gestation stalls or tethers. As expected, odour emission rates vary greatly between different types of animal production facilities, and even from the same facility over time (Wood et al. 2001). For instance, odour emission rates measured from various gestation barns ranged from 2 to 20 $OU/s/m^2$ (Jacobson et al. 1999b, Zhu et al. 1999). Environmentally controlled housing of breeding sows is the norm for modern pig production in Canada. This type of facility affords good control of odour-influencing factors such as manure, dust and mud, as well as reduced labour, better supervision of the breeding program, improved control of parasites, and a smaller required land base (MWPS 1983).

5.3.2 Farrowing

Farrowing facilities may be designed with one of a variety of management styles in mind (MWPS 1983). In small operations, sows may be farrowed once or twice a year, possibly on pasture. This allows for limited odour control opportunities, but the numbers of animals involved are usually small and may not make this an issue. In most Canadian pork-production operations, sows are farrowed indoors. Either a stall or a pen system may be used; pens allow for more sow movement but require more labour for cleaning. For ease of cleaning, all surfaces should be smooth in order to dry and drain more rapidly. Using slatted floors will reduce labour and provide a drier floor surface, but a solid covering must be used in the creep area for at least one week after farrowing (MWPS 1983). In large operations, two or more groups of sows may be farrowed as often as one group per week, each group being housed in separate farrowing rooms. This style of operation allows rooms to be emptied and disinfected between groups.

5.3.3 Nurseries

Nursery facilities house either weaned pigs or sows with litters. Fully slatted floors are highly recommended for nursery pigs. Thorough cleaning helps to prevent residual odour and reduce ammonia emissions from manure that might otherwise collect on pen surfaces. All-in, all-out practices allow for better disinfecting between groups of pigs and thus reduce the risk of disease. Decks may be used in the early or late-wean nurseries to increase stocking density, lower operating costs, and house fewer pigs per pen. However, pigs in the lower deck can be dirtier than normal, resulting in more odour. Also, care must be taken to provide the higher ventilation rates necessary for the increased stocking density, since elevated temperatures can exacerbate odour problems (MWPS 1983).

5.3.4 Growing/Finishing

Grower pigs consume 70% of the feed in pig production, and so the most opportunity for odour control is in feeder pig facilities. Growing and finishing operations may be open-front with an outside lot, modified open-front (naturally ventilated), or environmentally controlled with mechanical ventilation in the winter and possibly natural ventilation in the summer (MWPS 1983). Facilities with outside lots usually require more work than enclosed buildings, since manure must be handled as a solid with a scraper, loader, and spreader. Due to their larger, unenclosed surface area, lots also produce the most odour (MWPS 1983). In any case, this type of construction is generally unsuitable for very cold climates and is difficult to manage intensively. Modified open-front buildings are insulated and naturally ventilated, and may have fully or partially slatted floors. This type of construction also has limited applicability in cold climates. Environmentally controlled buildings are the industry norm in Canada, due in part to their suitability to the cold climate, and this is therefore the design type emphasized in this section.

Odour is related in part to the cleanliness of the animals, and good management practices are important in keeping the animals clean and odours at a minimum. Stocking density should not be excessive, since overcrowding leads to pen fouling. Feeder management can also affect odour production;

wasted feed adds to the organic load of the stored manure and contributes to the growth of moulds and the generation of foul odours.

Proper pen layout in a grower/finisher facility can do much to promote cleanliness and reduce odour problems. Open pen partitions in the dunging area encourage socializing and defecation in that area. Pigs can be encouraged to stay clean by installing cooling sprinklers over the dunging area for use during hot weather conditions. In a partially slatted floor plan, a step between the slats and solid flooring will help to define the dunging area (Alberta Pork and AAFRD 2002).

Good management is especially important with solid floors, since manure and urine are not separated from the swine (Yale Center for Environmental Law and Policy 2002). The best way to reduce the odour associated with solid floors is frequent cleaning. Manure that collects on the pen floor should be scraped into gutters daily (Alberta Pork and AAFRD 2002). Solid floors should be sloped toward gutters to facilitate waste removal.

The use of slatted floors is the simplest way to promote the separation of manure from animals. Floors may be partially or fully slatted, but there is little clear evidence as to how odour production relates to the percentage of the floor that is slatted. When floors are partially slatted, usually one-third of the floor area is slatted (Alberta Pork and AAFRD 2002). Bad dunging habits and inadequate manure storage can be problems with partially slatted floors. The use of fully slatted floors may reduce these problems, but the issue is confounded because more manure is usually stored in barns with fully slatted floors. Also, the relative contributions of odour from the slats themselves, the stored manure, other building surfaces and the animals are not known. It is clear, however, that slats that are easily cleaned by animal traffic will reduce manure accumulation and thus minimize the pigs' contact with manure (Alberta Pork and AAFRD 2002). The selection of slats with adequate void to surface ratios is therefore essential to pen cleanliness.

5.4 Mortality Disposal

The subject of odour emissions from mortality disposal sites seems to be limited to anecdotal evidence or practical discussion. No studies were found in the literature in which odour was measured in the vicinity of mortality disposal sites. From this, one would conclude that mortality disposal sites are not usually considered as important odour sources. One possible reason for this is that health regulations require that mortalities be properly disposed of within 24 to 72 hours (Fulhage 1994; Minnesota Board of Animal Health 1996). This does not usually provide enough time for a carcass to decay significantly and produce offensive odours. Moreover, mortalities are rarely generated in large quantities and are usually kept well within farm property boundaries until disposal. As well, mortalities are usually kept out of public view, and people are less likely to complain about an odour if they can't see the source (BC Ministry of Agriculture and Food 1978). Hence, proper handling and disposal of mortalities should resolve most odour problems. Advice for proper disposal is usually included in best management practice plans distributed by agricultural agencies.

5.5 Concluding Comments

a. The greatest opportunities for odour reduction are in pig production in growing/finishing facilities, where most feed is consumed and most manure is generated.

b. Good management practices are key to limiting odour emissions from any livestock production operation. Stocking density should not exceed the design rate, and pen surfaces should be kept clean and dry.

c. Proper facility design is important in odour control. In hog barns, slatted pen flooring and adequate floor slope allow proper drainage to help maintain clean, dry conditions. All-in, all-out systems allow for thorough cleaning and disinfection.

d. Mortalities should not lead to odour problems if they are disposed of promptly, and the holding site is well managed.

6 Cattle Feedlot Operations

The cattle feedlot industry has undergone numerous changes over the past 10 to 20 years. Feedlots with 25,000 head are becoming more common. Since they are highly integrated with crop production, these feedlot sites become part of a large parcel of land. This adjoining land produces the forage/grain and provides a land base for manure application during the spring and fall. The viability of the industry is tied to its attitude toward environmental and social issues. Protecting the receiving environment and minimizing the exposure of odour and bioaerosals to the neighbouring community will ensure a sustainable industry.

Current AOPA regulations specify manure management, manure storage, pen design and minimum distance separation criteria to reduce the risk of water contamination and reduce the incidence of odour nuisance conflicts. Under the act an "approval" is required to build or expand the following sizes of feedlots: a) > 350 beef cows (> 900 lb) and b) > 500 beef feeders (>900 lb).

Beneficial Management Practices: Environmental Manual for Feedlot Producers in Alberta (Alberta Cattle Feeders' Association and AAFRD 2002) outlines site selection criteria for feedlot development. The site must meet the development requirements of MDS, land base, soil and ground water assessment results. The design of pens, catch basins for runoff, and temporary manure storage sites must ensure that no contamination of ground water and surface water occurs.

As this manual discusses, a challenging aspect of feedlot design is to maintain pen surfaces that generate minimum dust and airborne particulate. This is particularly challenging during wet weather when wet manure produces odours and during hot weather when the pen surfaces are dry and generate dust as a result of wind and animal activity.

Three key practices are: a) scrap the pen surface regularly when more than 2.5 cm accumulate on the open surface, b) maintain moist conditions by increasing stocking density or sprinkling water on pen surfaces, and c) maintain smooth pen surfaces to prevent ponding of water during rainfall events. Odour and air particulate emissions can be reduced by discouraging animal movement during sorting times. Also, pen shape must be conducive to complete removal of manure from the pen surface.

Air quality adjacent to a feedlot was reported by McGinn et al. (2003). Average ammonia concentrations ranged from 130 $\mu g\ NH_3\text{-}N/m^3$ at a 6000-head feedlot to 813 $\mu g\ NH_3\text{-}N/m^3$ at a 12,000-head feedlot. They found that concentrations did not directly correlate with size (i.e. 6,000, 12,000 and 25,000 head). Stocking density had a larger effect on NH_3-N emission since more urine is volatilized per unit area. They also point out that the concentration must be multiplied by a larger area of the plume for the larger operations. Further investigation is required to estimate the mass transport of NH_3-N from a site. McGinn et al. (2003) also noted the concentrations of NH_3-N were high compared to other sources reported in the literature.

Of all the measured organic compounds, acetic acid accounted for the largest proportion of the volatile organic compounds (60%) followed by proprionic and butyric acid (McGinn et al. 2003). Odour concentrations measured by McGinn et al. (2003) were considered low. They were 20, 42, and 28 OU/m^3 for 6,000, 12,000 and 25,000, respectively. Low lying pens with standing water were reported to yield 170 OU/m^3 (Miner 1993). McGinn et al. (2003) also reported on total suspended particulates. The range of values for the three feedlot sizes over a 6-month period was 25.3 to 97.2 $\mu g/m^3$. They concluded that further research is required to evaluate the effect of short-term fluctuations on MDS values and the degree of odour annoyance.

Ammonia and butyric acid concentrations exceeded their individual thresholds as far as 200 m downwind from the feedlots. Findings reported by McGinn et al. (2003) also suggest that ammonia concentration may be a useful indicator of odour intensity from beef feedlots.

Research on diet manipulation has indicated that a possibility for reducing odours exists. Crude protein can be reduced thus reducing nitrogen excretion and therefore volatile ammonia (Paul et al. 1998). McGinn et al. (2002) report on a number of research projects that are attempting to reduce odour by improving the balance between rumen degraded intake protein and rumen fermentable organic matter. Also adding or subtracting specific amino acids to meet dietary requirements is a strategy to reducing total nitrogen excretion. McGinn et al. (2002) found that the ability to reduce (N) excretion was limited in balanced rations that yielded optimal growth.

Considerable research has been conducted on ammonia and odour emissions from manure spreading through soil tillage and injection management. In a literature review, McGinn et al. (2002) reported 30-50% reduction in ammonium N losses. Shallow channel application reduced losses by more than 90%. Since they reported a strong relationship between odour intensity and ammonium-N concentration, these practises are assumed to decrease odour emission rates by the same amount.

Stored manure (up to 9 months) can release significant amounts of odour and ammonia. Digestive additives, enzymes and manure additives do not appear to be effective in controlling odour (Warburton et al. 1981). This manure can be part of the feedlot surface or stored in temporary piles.

6.1 Concluding Comments

In summary, ensuring rapid surface drying, scraped feedlot surfaces, incorporation of manure into the soil or shallow channel application, and maintaining an adequate distance separation between the neighbours and the feedlot should reduce the incidence of odour nuisance complaints (McGinn et al. 2000).

7 Air Quality

7.1 Ventilation

Ventilation would seem to have a large influence on odour production, especially during extreme weather. For instance, ventilation rates in pig growing facilities range from a maximum during hot weather conditions of about 0.5 L/s/kg live weight to a minimum, during cold weather conditions, of about 10% of the maximum (Agriculture Canada Research Branch 1988). There is little research, however, to indicate that odour emission rates are in fact different at the two extremes. One can speculate that during periods of warm weather the low relative humidity of Prairie air will facilitate dry barn conditions. During cold weather, when ventilation rates are low and relative humidity values are high, moist surfaces in the barn may lead to an increase in odour. Improper ventilation can also increase odour emission rates by promoting poor dunging behaviour. In a facility with partially slatted floors, for instance, if the pigs are too warm they will excrete on the solid floor and lie in their feces to cool themselves. Conversely, during cold weather conditions, the pigs will excrete in the coldest area of the pen. If inlets direct cold air to the sleeping area, the animals will dung in the sleeping area, and they will be dirty and odorous as a result.

7.2 Heating

Poor design of the heating system can compromise the effectiveness of the ventilation system during cold weather. Sufficient heating capacity is necessary if proper inside temperatures are to be maintained while ventilating at an adequate rate. If animal facilities do not have sufficient heating capacity, a reasonable temperature can only be maintained if they are ventilated at a rate less than that required to control humidity. This will result in excessive moisture in the barn and high ammonia levels due to wet surfaces.

7.3 Ventilation of Manure Storage Spaces

Pit ventilation can help to reduce odour levels inside buildings with underfloor manure storage. The air that is drawn into the building to control temperature, humidity or air quality can be exhausted above the floor, below the floor (through the manure storage head space), or both. Improper ventilation design, however, might cause more odour to be transferred from the manure surface to the animal space than might otherwise occur. Furthermore, independent ventilation of the manure storage headspace appears to increase odour emissions from the facility as a whole, even though pit ventilation normally does not exceed one-third of the total building ventilation capacity (Borg 2001). A building incorporating vented manure head space is assumed to emit more odour than one in which the manure storage is not vented because, in the latter case, the manure headspace is stagnant. The cleanout operation is also of concern, especially if there is excessive agitation of the manure prior to removal.

7.4 Two-airspace Ventilation System

Feddes et al. (2001) reported on a two-airspace ventilation system that ventilated an enclosed dunging area separately from the worker/animal area. The enclosed dunging area was situated above the slatted area in a partially slatted floor configuration. The ventilation air entered the enclosed dunging area through doorways and was exhausted through a biofilter. The biofilter in such a system can be centralized in the building by way of ducts running the length of the building. The biofilter ventilation rate is 10% of the maximum summer rate (Canadian Farm Building Handbook, 1988). The remaining volume of the building is ventilated through the ceiling or the walls of the building. The gases/odours entering the enclosed cleaning area originate from manure attached to the slats or from the manure below the slots. The intent of this system is to store the manure for 9 months below the floor of the building. With a stagnant headspace above the manure storage, the emission rate of odours/gases is assumed to be less. One concern is that the ammonia content of the air exhausted from the enclosed dunging area can be high. This can compromise the operation of the biofilter.

7.5 Dust

Ventilation can be an effective strategy for controlling airborne dust within an animal barn. Most airborne particles in a livestock facility are in the respirable range (<5 μm) and therefore have a low settling velocity. On the one hand, airborne dust acts like a gas and very high ventilation reduces the dust concentration in the building (Gao and Feddes 1993). On the other hand, a very low ventilation rate results in higher humidity that reduces dust emission and increases the settling velocity of suspended dust. An optimum balance must be found between these two effects.

A significant source of odour emissions from confined feeding operations is from the animal production buildings. A confounding factor in determining the dispersion of odour is the role of respirable dust in concentrating and transporting these odours (Pabst 1998; Hartung 1985). Odours attached to airborne particulate may increase the persistence of the odour as it disperses away from the source (Bottcher et al. 2000). In two production units, the linear relationship between odour intensity and dilution ratio had a negative slope of about 0.5, while in another production unit the negative slope was 0.84. (The odour samples with a slope of –0.5 are more persistent than the steeper slope of –0.84.) The difference was attributed to different dust concentrations.

Jacobson et al. (1999) evaluated the odour and gas reduction potential of soybean oil sprinkling for airborne dust control in a pig nursery. They used the dosage recommended by Zhang et al. (1996), which applied 40 mL/m^2 for the first 2 days, 20 mL/m^2 for the next 2 days and a 5 mL/m^2 "daily maintenance" level for the remaining days. The oil was sprinkled in the barn with a hand-held commercial paint sprayer. There was a significant reduction in their first trial. In their second trial, the outdoor temperature increased, causing higher ventilation rates. There appears to be less odour reduction during higher ventilation rates, which may have coincided with poor dunging behaviour.

Feddes et al. (1999) used a similar oil dosage whereby one dosage was 60 mL/m^2/week and the other dosage was 30 mL/m^2/week. With the 60 mL/m^2/week application, odour concentration was reduced by 20%, whereas the 30 mL/m^2/week resulted in no reduction in odour concentration. They also suggested that sprinkling oil on the floor surfaces only removes the odorous dust particles originating from the solid surface of the floor. Since 75% of the respirable dust was removed, a large amount of odour appears to be generated by the slatted area where little dust is generated due to the moist surfaces. Payeur et al. (2002a) found no relationship between dust concentrations and odour emissions. They applied canola oil at a rate of 0 and 10 mL/m^2/day.

Godbout et al. (2000) described their experiment to reduce odour emissions by sprinkling canola oil. They applied 31 mL/m^2/day, a much higher rate than applied by Feddes et al. (1999), and obtained a 90% reduction in respirable dust. Godbout et al. (2000) did not report any odour emission data. Takai et al. (1993) used a mixture of water and rapeseed oil (5 – 30 mL/pig/day). Respirable dust levels were reduced by 76, 54 and 52% for buildings housing piglets, young pigs and fattening pigs, respectively.

Wang et al. (1998) found that a synthetic dust particle, Tenox, was a superior adsorber of volatile fatty acids and p-cresal when compared to the feed/fecal particles. This suggests that the particle types that are airborne have different affinities for the odorous gases. Indolic compounds were not adsorbed by the synthetic or the feed/fecal airborne particles.

Bottcher et al. (2001) evaluated and observed windbreak walls for tunnel ventilated livestock buildings. Windbreak walls were placed near exhaust fans to divert the exhaust air upwards. This effect promotes larger plumes of dust and odour at the source. They also suggested wall placement and wall design considerations. Hoff et al. (1997) evaluated biomass filters for reducing odorous dust emissions. Exhausted odorous air was forced through panels of biomass. They did obtain high dust and odour reductions.

Auvermann et al. (2001) reviewed the state of knowledge concerning the sources, emissions and control of particulate matter (PM) from confined animal feeding operations. An increase in slatted floor area may reduce PM emissions, especially with increased stocking density. The increased hoof action pushes the manure accumulations into the pits or flush gutters below rather than leaving it on the surface to dry and be re-suspended (Auvermann et al. 2001). These authors suggested that dust control technologies need further investigation. For example, air ionization appears promising and with the development of technology in general, this technology may be economical, reliable and safe compared to when this technology was first introduced.

Pedersen (1993) found a correlation of 0.66 between animal activity and airborne dust concentration. His results suggested that the correlation would strengthen as the level of activity is better defined. Pedersen and Takai (1997) and Feddes et al. (1999) showed that dust is an important carrier of odour. Carbon dioxide and heat production and dust release show similar diurnal variation (Pedersen 1993; Pedersen and Takai 1997). During the non-active periods, ventilation of the animal house would be lowest, while during the day activity levels are highest and ventilation rates are the highest. Based on these results, Schauberger et al. (1999) concluded that odour release rates are not constant over the day. Thus, separation distances cannot be based on a constant odour release. The diurnal variation of odour concentrations of the exhausted air can range up to a factor of 6 with the maximum value during the night and the minimum during the day. If dust is an important carrier of odour, then the diurnal fluctuations in dust concentrations are an important part of predicting odour concentrations and emission rates over a 24-h period.

Hoff et al. (1997) cited literature that indicates that odour is amplified by the presence of dust particles. Odour in the absence of dust particles reduces in intensity much faster with dilution when compared to odour in the presence of airborne dust particles. Heber et al. (1988) found that in 11 monitored swine barns, particle counts indicated that 93% of the airborne particles were smaller than in 5.2 microns. This dust has a low settling velocity and a high proportion of the surface area compared to the larger particles. This suggests a longer contact time between the particle and odours in the air. Also, many of the respirable dust particles are thought to be of fecal origin since they breakdown readily and have a high protein content relative to feed particles.

In cattle feedlots, airborne dust from feedlot surfaces can impact neighbours. The highest exposure is expected to be between dusk and sunrise when the atmosphere is the most stable. There is little mixing of the dust with the atmosphere, so that the dust moves as a cloud downwind from the feedlot operation. Again dry, loose manure must be regularly removed from the surface. Sprinkling the feedlot surface may have to be an option.

7.6 Concluding Comments

a. Adequately designed heating and ventilation systems can help to maintain a good barn environment and limit odour and dust emissions. Vented air may be discharged either vertically or horizontally, but there is little indication in the literature of optimal design for odour control.

b. Heating capacity must be sufficient to allow adequate ventilation rates in winter.

c. There are conflicting claims regarding the effect of pit ventilation on odour emissions. It may reduce indoor odour but increase overall facility emissions.

d. Dunging areas can be enclosed and independently ventilated to help control odours.

e. Dust emission rates can be reduced by up to 75%; however, little odour reduction results. The majority of the odour molecules are not attached to dust particles.

f. The effect of dust removal on odour character and persistence is not known.

g. Some data suggest that ammonia and odour concentrations are independent of odour intensity.

h. Animal activity affects both odour and dust particle production.

i. Odour in the absence of dust has a decreased persistence.

8 Manure Handling

8.1 Gutter Systems

Manure handling in facilities that house large animals frequently relies on gutters. A gravity drainage gutter system uses little or no water and relies on gravity to move manure from open-floor gutters into storage units (Yale Center for Environmental Law and Policy 2002). Such a system is used where minimal waste volume is desired (Meyer 1990).

Some producers who adopt a solid-manure management strategy use a mechanical manure removal system in their gutters. Open channel scrapers and under-slat scrapers have both been proven to be reasonably effective and are easily adapted for use in most existing buildings (Dickey et al. 1996). Scraper systems can be problematic with respect to odour because ammonia and odour levels tend to rise if residual manure is left in the gutters (Dickey et al. 1996). Solid manure handling is further discussed below.

In gutters designed for liquid manure handling, a flush system is often used. Manure is collected from under-floor pits or open-floor gutters and discharged into manure storage facilities such as tanks, basins or lagoons. Manure can be removed on a daily basis or more frequently (Miner 1995). Gutter floors should slope at 1-2%; a minimum flow of 1 m/s (3 ft/s) with a discharge duration of 10 s is adequate for most buildings (Yale Center for Environmental Law and Policy 2002). The advantages of flushing open gutters are lower odours within the building, quick manure removal, and lower construction costs (Dickey et al. 1996). The animals have easy access to the gutters and establish regular dunging patterns that facilitate manure movement. However, cleanliness is an issue, and there is also increased risk of disease and drug transmission (Dickey et al. 1996). Neither are flushing systems suitable for all types of facilities; for instance, the floors of gestation barns cannot be flushed (due to slipperiness of the surface) but open-floor gutters in these buildings can be flushed. Liquid manure systems are further discussed below.

8.2 Solid Manure

Manure in solid form includes litter from poultry (turkeys, broilers), separated or scraped solids from dairy and pigs, manure collected from beef feedlots, hoop structures housing growing pigs and loose housing using straw bedding for dairy cattle. Less bacterial action is present in the drier forms of manure, thus less odour production per unit volume (MMSC 2002). Also, there appears to be less objectionable odour from bedded/litter systems, when the moisture content is reasonable. In bedded systems that have a high stocking density, the rate of evaporation may be inadequate to evaporate the animal contribution, thus it becomes a moisture sink. Bedding with excessive moisture along with the disturbance from animal activity can generate excessive odour emission rates.

A number of swine grower-finisher facilities are managing manure as a solid (Coleman 2002; Luymes 2001). Bedding in the form of shavings or straw is added to a sloped solid floor to absorb urine and feces (Alberta Pork and AAFRD 2002). This kind of system is commonly used in pig finishing facilities, and gestating females often are also housed in bedded pens (Alberta Pork and AAFRD 2002). New bedding is added to the pens as needed, and the pens are cleaned after every batch of finished hogs or, for sow housing, on a regular schedule (Alberta Pork and AAFRD 2002). The bedding material moves towards the end of the pen where the manure is moved out of the building by a conveyor or a motorized scraper. Once the material is outside the building, it goes through a composting process. As DGH Engineering Ltd. states in its review, this method of manure handling creates an aerobic environment resulting in less offensive odours (Zhang et al. 2002). However, more ammonia is generated as the manure dries in the building. The additional cost of straw is also a concern, along with the labour cost of handling the manure. To minimize potential odour, it is important that enough straw be used to absorb liquid waste and that the condition of the bedding be checked on a daily basis. For growing pigs, straw requirements are estimated to be 90 kg per pig (Zhang et al. 2002). The use of straw in gestation and farrowing facilities is not well documented.

As with other animal production operations, cattle feedlot surfaces must be kept hard, smooth, and as dry as possible. A 2-5 cm base of compacted manure should be maintained above the compacted base (MMSC 2002). Corral enclosures must shed water rapidly to avoid water storage in the compacted material. Operators must receive training to appreciate the importance of the compacted base and compacted manure. Feed can have a significant impact on odour in feedlots if protein is overfed or sulphur-containing amino acids are overfed or water contains excessive sulphate.

8.3 Liquid Manure

8.3.1 Indoor manure storage

The trend to combine manure storage with animal production buildings is increasing. Since manure is considered a fertilizer resource, it is stored during the period when land application is not permitted. Over 90% of the pigs produced in Canada are reared on slatted floors where the manure is stored beneath concrete slats in a liquid form. Slatted floors often cover a collection pit where animal waste and wash water will collect (Dickey et al. 1996). Collection pits are usually the full width of the slatted area in the pens (Alberta Pork and AAFRD 2002). Under-floor storage pits are generally shallow, but deep pits (2.5 m or 8 ft) may also be used (Alberta Pork and AAFRD 2002). Pit dividers channel manure through plugs that discharge into pipes that take manure out of the barn. Under-floor storage is often combined with anaerobic lagoons or other outdoor storage units to accommodate pit overflow (Dickey et al. 1996). Manure is stored temporarily beneath the slatted floor, then discharged to a 9-month outside manure storage.

Although pits reduce labour and the potential for water pollution, they do pose a potential problem with respect to odour and gases. The composition of the manure is normally 90-95% water. Since the manure is very organic, this medium provides an excellent habitat for anaerobic micro-organisms. The digested end products are very odorous since they are produced primarily by acid forming bacteria. Deep pits typically produce less odour than shallow pits. As mentioned, there are odour and safety issues regarding the ventilation of the manure headspace and the release of dissolved gases during the cleanout operation (Dickey et al. 1996; Miner 1995). Extended manure storage within the building air space may also have implications for worker and animal health.

8.3.2 Outdoor manure storage

Outside manure storage can be above ground in a unit such as a metal or concrete tank or below ground in an earthen or concrete storage. The manure can be pumped into the bottom or top of the storage. Top loading can severely agitate the contents of the storage and accelerate the release of trapped odorous gases in the liquid.

Lagoons are commonly used to store and biologically treat liquid manure. As well as providing storage space for manure during seasons when it cannot be land applied, lagoons also reduce the nutrient mass of the manure. Phosphorus settles and is sequestered on the lagoon bottom for many years, and nitrogen is volatilized as a gas (Lorimor et al. 2001). Bacteria in the lagoons convert volatile solids into liquids and gases such as methane and carbon dioxide (Miner 1995). Dilution of the manure slurry in the lagoon with water promotes microbiological digestion and reduces the ammonia concentration that can impede digestion. This minimizes odours and reduces the concentration of solids in the lagoon (Yale Center for Environmental Law and Policy 2002).

Lagoons may be either aerobic or anaerobic, the latter type being the most common. Anaerobic lagoons emit odorous gases including ammonia, hydrogen sulphide, methane, and other volatile organic compounds (Lorimor et al. 2001). Anaerobic lagoon systems may be single or multi-stage, but most lagoons in the Canadian Prairies are single-stage. In warmer climates, however, multi-stage systems may provide better odour control. The first stage is the primary treatment unit where organic material is allowed to stabilize, and the second and subsequent stages contain relatively clean water, which can easily be pumped for use in flush systems or applied to cropland. Multi-stage systems make the removal of sludge and effluent easier (Yale Center for Environmental Law and Policy 2002).

In aerobic lagoon systems there is enough free oxygen to sustain aerobic bacteria by virtue of either a large surface area (passive aeration) or mechanical aerators (Yale Center for Environmental Law and Policy 2002). This makes aerobic lagoons more costly, but they produce less offensive odour. A passively aerated lagoon depends on wind or algal growth for the oxygen supply and so its depth is limited to about

1.5 m (5 ft). When a mechanical aeration system is used, a portion of the organic load is usually removed by sedimentation or screening out the solids (Miner 1995). A mechanically aerated lagoon can be deeper than a passively aerated one, typically 2.5 to 6 m (8 to 20 ft) (Lorimor et al. 2001).

A well-designed and well-managed aerobic lagoon will emit only a slightly musty smell. A foul odour indicates a malfunction, probably caused by too high a loading rate (Tyson 1996). The recommended loading rate for an aerobic lagoon is 90 to 180 L/kg of pig (1.5-3.0 ft^3/lb) (Miner 1995). Loading rates can be increased as the outside temperature increases because bacteria are more active in warmer weather. During spring warm-up, bacteria must stabilize excess organic matter, and this results in the production of large amounts of biogas and odour (Heber and Ni 1999). A lower loading rate should be maintained during this time. This can be achieved by adding smaller amounts of waste more frequently (at intervals of less than a week), separating solids from liquids, or land spreading some liquid when possible (Heber et al. 1999).

Some technology is available to aerate the surface of a manure storage. The surface of the storage is aerated so that odorous compounds produced in the anaerobic zone pass through the aerobic layer and, in theory, are oxidized into odourless compounds. In a recent study conducted by the Universities of Alberta and Saskatchewan, however, surface aerators appeared to generate more odours in the spring and less in the fall than a non-aerated surface. Over the season, both systems generated the same amount of odour. The aerators appeared to facilitate the release of odours by mechanical agitation rather than reducing the odours due to aerobic microbial activity. As a result, fewer odours would be mechanically flushed from the stored manure towards the end of the season (Edeogu 2002).

Other ways to keep odour in check are by agitating the first stage lagoon in a multi-stage system and removing sludge every 3 to 4 years to reduce buildup. As well, high pH (more than 6.5) increases the activity of methane bacteria, decreases the acid concentration, and reduces odours (Tyson 1996). The addition of hydrated lime will increase the pH if it is too low, although this will not be effective if the lagoon is overloaded. Another option is to plant trees around the lagoon to channel odours upward into the air for greater dilution and dispersion (Heber et al. 1999).

8.3.3 Storage covers

Covers can reduce odour from outdoor manure storage facilities by limiting solar heating and wind-induced volatilization. There are several types of covers, including natural crusts, solid covers, impermeable floating covers, and biocovers. A natural crust forms, for example, on manure from swine fed a high-fiber diet (such as barley-based diets). Such a crust may reduce odours by half (Heber et al. 1999). Solid covers will almost completely reduce odour (Table 1) but are very expensive. Impermeable floating plastic covers will reduce odour by up to 99% (Heber et al. 1999), but are also expensive ($0.35-0.45 per market pig) and therefore have not been widely adopted. Impermeable covers can also be combined with a ventilation system so that a negative pressure zone is maintained beneath the cover. In this way any gaseous emissions that collect under the cover are vented, and the cover is drawn down to the surface of the manure to prevent wind damage (Danesh et al. 2000; Li et al. 2000). The air exhausted from beneath the cover can be treated by biofilters to remove the odour constituents. The volume of vented gas is much less than would otherwise be released from an open lagoon. In a more comprehensive strategy, the vented gas could be treated with a biofilter to further reduce total odour emissions.

Permeable covers, such as biocovers, are another effective option (Clanton et al. 2001; Mannebeck 1985; Miner 1995). Biocovers are perhaps the more cost-effective and farmer-friendly means of reducing odour from outdoor manure storage facilities. Gas concentrations build up under the cover, keeping most of the gases in solution (Bicudo 1999). This kind of cover also acts as a biofilter because it provides a large surface area within the cover material and conditions for the growth of aerobic microbes. The microbes degrade odour compounds and other gases emitted from the slurry (Heber et al. 1999). The cover is usually composed of organic material (e.g. wheat straw, barley straw, chopped cornstalks, sawdust, wood shavings, rice hulls) that is blown onto the surface of the storage in a layer about 250 mm thick (Bicudo 1999). Straw can be wetted with manure slurry to make it more biologically active and promote biofiltration (Zhang et al. 1999). Straw is easy to apply but may need to be reapplied because it will sink over time. It should be replaced every 2 to 3 months. Finally, when the manure is spread, the straw is mixed and applied along with it (Zhang et al. 1999). The straw should therefore be well chopped because

Table 1. Covers for outdoor manure storage

Type	Construction	Advantages	Disadvantages	Cost
Solid Covers	Steel Concrete Wood	Almost complete Long lasting	Expensive	$50,000 (concrete)
Flexible Covers	Anchored tarp Domed tarp with low-pressure blower	95% odour reduction Long lasting (10 to 15 y) Easy to remove	Expensive Some maintenance required	$10,000 initial cost, $200/yr operation
Unsupported Organic Covers	Blown onto storage with forage harvester Quality barley straw works best Added peat moss improves nutrient intake in the field	Inexpensive Effective odour control	Repeat applications of straw may be necessary Straw may interfere with pumping	150 mm barley straw (at $1.00 per small square bale): $0.23/m^2
Supported Organic Covers	Polystyrene pellets applied prior to the barley Oil added to the straw to increase durability	Effective odour control Fewer straw applications required Polystyrene pellets can be collected and reused	Expensive Recovery of floatation devices can be difficult	125 mm barley straw and 25 mm polystyrene: $2.45/m^2

Source: Cetac-West (1999)

large pieces may interfere with pumping equipment. The life of a biocover can be extended with the use of a geotextile fabric or other buoyant material, such as polystyrene pellets (Jacobson et al. 1999a). Straw may be mixed with vegetable oil to help keep the cover afloat longer (Barrington 1997; Schmidt 1997).

A cover comprising 200 to 300 mm (8 to 12 in.) thickness of chopped barley, wheat, oat or brome straw gives 50 to 80% odour reduction. Bicudo (1999) estimates that a 250-mm straw cover can reduce odour, H_2S and ammonia from swine manure tanks by over 80%. Schmidt (1997) investigated several styles of covers in small storage tanks and found that odour reduction with straw was from 72 to 84% and hydrogen sulphide reduction was from 82 to 94%. Zhang et al. (1999), however, estimated an odour removal efficiency between only 35% and 55%.

Although the price of straw is quite variable, Zhang et al. (1999) estimated the cost of a straw cover on an open manure storage unit to be between CAN$0.10 to and CAN$0.50/m^2. Heber et al. (1999) estimated a cost of about $0.10 to $0.20 per m^2 ($0.01 to $0.02 per ft^2). Jacobson et al. (1999a) list the cost of a 300 mm (12 in.) cover of straw as $0.85 per m^2 ($0.08 per ft^2), not including application.

Some examples of the cost of synthetic covers are: clay balls (US$21.50 to US$53.80/m^2); geotextile (US$1.07 to US$4.30); and plastic sheeting (US$10.76 to US$21.52/m^2) (Jacobson et al. c.1997).

8.3.4 Liquid-solid separation

Liquid manure contains high levels of settled and suspended solids (5-10%). Liquid-solid separation can occur by gravity (6-24 hr) or mechanically by screening or centrifugation. In a study at the University of Alberta, enhanced flocculation through the addition of alum, gypsum or lime did not result in more solids settling than natural settling over a 24-h period (Navaratnasamy et al. 2002). The separation of solids, especially in anaerobic environments, leaves many suspended solids acting as colloids, where they remain in suspension due to particle charge. Many of these particles are organic in nature, leaving much of the odour-causing potential in the liquid fraction. The separated solids appear quite inert, with grain hulls, non-digestible matter and dicalcium phosphate being most prevalent in the liquid-solids separation trials at the University of Alberta. Liquid-solid separation of aerobic manure results in a higher organic content in the solids fraction. Bacteria metabolize the small colloidal particles and convert them to cell mass that settles out of the liquid.

Navaratnasamy (2002) found that low-level aeration of the liquid fraction was very effective in removing suspended solids. By removing the suspended solids from the liquid fraction, the odour emission rate should decrease.

Storing only the liquid fraction in earthen manure storages appears to have long-term benefits. From observation of earthen manure storages, storages with no separation of solids have mats of solids continuously rising to the storage surface and releasing large amounts of gas. In earthen manure storages where the settled solids have been removed, little surface disturbance is observed and odour emissions are thereby reduced. Effective liquid-solid separation also serves as a pre-treatment to facilitate the transport of more concentrated manure.

8.4 Land Application

8.4.1 Surface spreading

Tank wagons or drag-hose systems are often used with surface application equipment to land-apply manure slurries. There are various practices that can help to reduce odour emission from land application operations. These may be as simple as: maintaining a minimum distance between the spreading location and the neighbours; spreading during calm periods or when the wind is blowing toward uninhabited areas; or spreading when neighbours are less likely to be home (e.g. weekdays).

8.4.2 Irrigation

Irrigation systems are used throughout much of the United States to land-apply lagoon liquids. Big gun and center pivot irrigation systems are popular for this purpose (Lorimor et al. 2001). Although irrigation is also sometimes used as a method for spreading slurry liquids, they are not as well suited to this purpose. Slurries have higher solids content and tend to be more odorous than lagoon effluents (Yale Center for Environmental Law and Policy 2002). Also, the odour potential during land application with irrigation equipment is especially high (Dickey et al. 1996); spraying produces small droplets which can volatilize and migrate great distances (Yale Center for Environmental Law and Policy 2002). Low pressure, downward pointing nozzles on drop pipes can help to minimize odour emissions from effluent irrigation (Lorimor et al. 2001). Another drawback to irrigation systems is that, when pumping from a fixed source, friction losses and pumping costs limit their use to a practical radius of about 3.2 km (2 mi.) from the storage site (Lorimor et al. 2001).

8.4.3 Incorporation

Rapid incorporation of applied manure into the soil helps to reduce odour problems. Manure should typically be incorporated within 12 h of application to ensure minimal odours as well as maximum nitrogen retention (Yale Center for Environmental Law and Policy 2002). Equipment such as ploughs, rotary harrows or tines may be used for incorporation. In experiments undertaken in the Netherlands it was found that, on arable land, ploughing immediately after application reduced the odour emission rate during the first hour by 85% and by 52% over 48 h.

Rotary harrowing reduced odour emissions during the first hour by 45% (Pain et al. 1991). When incorporation was delayed for more than 3 to 6 h after application there was no reduction in total emissions. However, tillage buries the crop residue, increasing the risk of soil erosion.

8.4.4 Injection

Injection is the most effective way to reduce odour emissions from the land application of manure (Yale Center for Environmental Law and Policy 2002). Manure has traditionally been injected into the soil using equipment with injection knives spaced 0.75 to 1.5 m (30 to 60 in.) apart. Manure is injected into the soil in a concentrated vertical band 150 to 200 mm (6 to 8 in.) below the soil surface. Newer equipment, such as sweep and disc injectors, can also spread manure horizontally under the soil surface, allowing for the faster breakdown of the manure (Yale Center for Environmental Law and Policy 2002). However, injection loosens crop residue and the soil surface, creating some risk of soil erosion.

8.5 Concluding Comments

a. Facilities with manure handling systems such as flushing gutters, or slatted floors and under-floor manure storage pits, allow for containment of manure odour and good pen hygiene. These systems allow thorough cleaning of the pens.

b. Solid manure has a lower level of microbial activity because of its dryness, whereas liquid manure provides an excellent habitat for microbial activity and can hold odours in gaseous form. Consequently, when agitated, large amounts of odour can be emitted from liquid manure.

c. Feedlot surfaces require regular cleaning and careful management to minimize odour emissions during wet periods and airborne particulate emissions during dry periods.

d. Emission rates from stored manure within buildings relative to those from outside manure storage facilities are not clear. Also, the relative odour emissions from solid floors, slatted floors and stored manure surfaces require investigation. The relationship between ventilation rate and odour emission rate has not been documented.

e. Some large, new pig facilities with inside manure storage pits have reported high levels of hydrogen sulphide when the pits are drained. The manure drainage system is not sized to accommodate this initial surge of manure when the pits are emptied, and manure plugs in neighbouring rooms can be dislodged and allow manure gases to escape. The design of barn manure drainage systems might be revisited based on the principles of open channel flow common in municipal sewage systems, rather than relying on full pipe flow.

f. Liquid manure storage lagoons are less odorous if designed to be aerobic rather than anaerobic, but this makes them more expensive to build and maintain. Anaeorobic lagoons must not be overloaded with solids. Lowering the solids content of the liquid manure in storage, lowers gas emission due to the decreased activity of settled and suspended solids which are buoyed to the surface by gases attaching to them.

g. Covers reduce odour emissions from manure storage lagoons. The negative pressure cover shows promise, but removing plastic covers during manure removal is awkward. Chopped straw is an effective and economical alternative. Planting treed windbreaks and using additives to control pH in the lagoon when necessary may also be useful management options.

h. Liquid-solids separation can reduce odour emission rates and facilitate more economic transport of concentrated manure. There also appears to be an option to recycle 80% of the treated liquid fraction to the animals for drinking purposes. This requires further investigation.

i. Direct injection is the best way to limit odour emissions when land-applying liquid manure. Rapid incorporation can help to alleviate odour problems when surface spreading.

j. From this literature review, documented data on odour emission rates from different types of storage and treatments are lacking. Manure handling and control technologies cannot be evaluated if odour emission rate data are not available. Odour emission data are lacking for the following:

    i. Liquid manure storage, relative to: separated, non-separated, and agitated storage

ii. Solid manure storage, relative to: temperature, moisture content and differences between dairy, beef, poultry, and swine manure

iii. Indoor storage, relative to: odour contribution from slats, solid floor, and storage

iv. Ventilated vs. unventilated pit storage

v. Alternative protein- and sulphur-reduced diets

vi. Straw and impermeable covers for lagoon storage

k. Widely accepted protocols need to be developed to measure odour emission rates from liquid surfaces or irregularly shaped manure surfaces.

9 Emerging and Alternative Technologies

9.1 Diet Manipulation

Diet manipulation can be effective in reducing manure odour. Protein reduction reduces ammonia production (Payeur et al. 2002). Providing animals with maintenance diets will reduce odours but this, however, is not a profitable option. For animals to be gaining at their genetic potential, their feed must be high in energy and protein. Research is ongoing at the University of Alberta to find synthetic amino acids to add to the ration, that will result in a lower protein content and yet supply the essential amino acids required for optimal growth (Ball 2002). The impact of excessive sulphur-containing amino acids and the sulphur content of the drinking water content on odour and hydrogen sulphide emissions is not clear.

9.2 Manure Additives

Manure additives to control odour include masking agents, counteractants, digestive and chemical deodorants, and absorbents. Masking agents have a stronger odour than the original odour and can sometimes be just as offensive due to their intensity (Yale Center for Environmental Law and Policy 2002). Additives that decrease the ammonia and solids content of manure can reduce odour by 70 to 84% (Cetac-West 1999). However, research results are in conflict with respect to the effectiveness of these additives, and some studies cast doubt on the validity of commercial claims. Some additives appear to change the hedonic tone of the odour, but not necessarily the odour concentration (Lemay et al. 2002).

Alkaline reagents, such as various types of kiln dust, fly ash, and lime products, have been found to reduce odour emissions from earthen and concrete manure storage facilities (Messenger 1996). Field studies undertaken at the University of Iowa evaluated several of these reagents. The additives were mixed with manure in an 11,350 L (3000 gal.) tank at a rate of 0.3 kg per kg manure solids (0.3 lb per lb manure solids). An 80 to 90% reduction in manure odour levels was reported for some additives (Messenger 1996). Nevertheless, the marketing claims that are made for commercial products should always be evaluated with care.

9.3 High Temperature Anaerobic Digestion

The anaerobic decomposition of manure by bacteria results in organic matter that has significantly less odour than non-digested waste, although the volume of manure is not significantly reduced by digestion (Yale Center for Environmental Law and Policy 2002). The biogas generated during this process comprises methane (50-80%), carbon dioxide (20-50%) and trace levels of other gases (Yale Center for Environmental Law and Policy 2002).

Biogas generation is not economically feasible as an odour control technology alone. It may, however, be a practical option in areas where the price of waste disposal and energy make possible some accompanying cost recoveries. Although the commercial production of biogas from animal manure is currently not widespread in North America, it became popular in Denmark and Switzerland in the 1970's when oil prices were high (Yale Center for Environmental Law and Policy 2002). High temperature anaerobic digestion has been extensively investigated over the last 30 years as an energy source for heating or electrical production. Biogas can be burned directly as fuel in heaters or combustion engines during continuous operation; however, engine corrosion occurs when operating below normal coolant temperatures. This presents a problem when the supply of biogas is not sufficient to operate an electrical generator continuously (Moser 2000).

The generation of biogas involves some inherent operational challenges: starting the process is difficult and constant monitoring is required thereafter to ensure optimal conditions; it cannot be used in operations where antibiotics are added to the animal feed; and the storage of biogas is difficult (Yale Center for Environmental Law and Policy 2002). An industrial scale anaerobic digester outside the Iowa State University was installed to reduce the minimum separation distance (Moser 2000). The by-products of acid forming bacteria are very odorous but, in this digestion system, these by-products are metabolized by methane forming bacteria. At lower temperatures, however, the rate of organic acid and alcohol production overwhelms the metabolism rate of the methane forming bacteria, resulting in an odorous process.

The thermal requirements of the anaerobic digestion process have been reviewed. In cold climates, the vessels must be well insulated or placed below grade. In installations where the methane is converted to electrical energy, the engine coolant is circulated through a heat exchange pipe located in the digester, where sufficient heat energy is reclaimed to meet the thermal demand of the process when maintained at 35^0C (Moser 2000).

9.4 Oligolysis

Some research has been conducted using oligolysis as an odour control mechanism (Coleman et al. 1994). In this process, a steel cathode and anode are placed in the manure, and a direct current is passed between the two electrodes. The ferrous ions traveling from the anode to the cathode react with the sulphur-containing compounds in the manure. The odour levels were found to decrease as a result, but the amount of power required to accomplish this was unreasonable.

9.5 Ozonation

Ozone has been used to oxidize odorous metabolites to reduce odour emissions. Wu et al. (1999) have had success in reducing odours by bubbling ozone-enriched oxygen into pig slurry. Because of the high organic load of manure slurry, however, ozone consumption is expected to be excessive.

9.6 Disinfection of Wastewater

Chemical disinfectants such as chlorine, ozone, and hydrogen peroxide are effective in treating dilute wastewater (Zhang et al. 2002). The effectiveness of disinfecting manure to suppress odour has not been well documented. The chemical requirement for effective disinfection appears to be very high, and offensive odorous compounds such as chloramines can result from the disinfection process.

9.7 Concluding Comments

a. Diet manipulation appears to impact odour emission rates. By optimizing the nitrogen and sulphur-containing amino acids, NH_3 and H_2S levels may be reduced. This requires further investigation.

b. There are conflicting research results about the efficacy of manure additives in reducing odour. Manufacturer's claims are sometimes exaggerated and must be considered carefully.

c. Oligolysis, ozonation and disinfection of wastewater appear to require excessive amounts of power or chemical inputs.

d. High temperature anaerobic digestion requires investigation for Alberta. This technology provides odour control and a source of electricity. Based on a recent tour, the technology has advanced significantly since the 1970's.

10 Biofiltration

10.1 Background

Biofiltration, in the context of exhaust air treatment, is a technology in which air is passed through a packed bed of warm, moist, nutrient-rich, porous filter medium prior to emission into the atmosphere. The filter medium provides a suitable environment for the growth of microbial films. Many volatile compounds that are carried in the air stream diffuse into the microbial films and are metabolized (Alonso et al. 1997). Biofilters effectively reduce concentrations of ammonia, hydrogen sulphide, methyl mercaptan, dimethyl disulphide, and other reduced sulphur-based and nitrogen-based organic compounds found in livestock odours (Easter and Okonak 2000). The principle metabolites are carbon dioxide and other non-odorous gases, water, and mineral salts (Williams 1993). The degradation of contaminant compounds in biofilters occurs at normal temperatures and pressures, so biofiltration is economically competitive with other emission control technologies (Alonso et al. 1997).

Biofilters are especially effective when used to treat large volumes of air containing low concentrations of contaminant compounds, such as ventilation exhaust streams from enclosed livestock operations (Otten and Gibson 1994; Janni and Nicolai 2000; Goodrich and Mold 1999; Nicolai and Janni 1997; Noren 1986). For instance, low-cost, open-bed compost biofilters reduce odour concentrations from swine barn ventilation air by 75 to 90% (Nicolai and Janni 1997). Compost and brush chip biofilters tested at a swine facility over a 10-month period achieved odour removal efficiency of about 90%, hydrogen sulphide removal efficiency of 96%, and ammonia removal efficiency of more than 75% (Janni et al. 1998).

The number and size of intensive livestock operations is growing, manure storage units are increasing in size, and manure storage times are lengthening (Jacobson et al. 1998; Barrington 1997). There is also a shift to the injection-spreading of manure so that, overall, more odour complaints are traceable to animal production facilities and manure storage units, and fewer to the land application of manure (Jacobson et al. 1998). Biofiltration is becoming more relevant to the livestock industry because it is suitable for treating odours from confined sources (buildings and storages) as opposed to distributed sources (land application). This report focuses on the application of biofilters to swine housing and manure storage units, but the information is applicable to the cattle and poultry industries in general.

10.2 Operating Conditions

The effectiveness of a biofilter is maximized by maintaining preferential conditions for the growth of the appropriate microbes. These conditions include temperature, moisture, nutrient availability, and acidity.

The naturally occurring micro-organisms that most effectively degrade odour compounds are mesothermic bacteria. The temperature range for biofiltration, therefore, is from 15°C to 40°C (Burrowes et al. 2001), with the optimum temperature between 30 and 40°C (Janni and Nicolai 2000; Leson and Winer 1991). Biofilters associated with agricultural operations generally do not need supplementary heat to maintain these temperatures: the heat from the exhaust air and exothermic microbial activity in the filter bed is usually sufficient to keep the filter bed in the right temperature range, even in cold winter climates (Janni 2000; Mann et al. 2002).

The support of microbial populations sufficient to reduce odours requires that moisture levels in the filter medium be maintained between 40 and 70% (dry basis) (von Bernuth et al. 1999). Too much moisture plugs pores in the filter, causing channeling and limiting oxygen availability (Nicolai 1998). As well, if the filter is too wet, there is the risk of compaction of the filter medium, resulting in low porosity, high back pressure, compromised air flow, and excess volumes of acidic leachate (Swanson and Loehr 1997). On the other hand, if the filter is too dry there will be insufficient microbial activity, and cracking or channeling in the filter bed (Nicolai 1998). Dry air is especially problematic if the inlet airflow is cold, because moisture will be stripped from the filter medium as the air heats.

Most commonly available organic biofilter media will provide sufficient nutrients for the degradation of odour compounds (Leson and Winer 1991). Some reports indicate, however, that the degradation of compounds such as hydrogen sulphide might be enhanced by the addition of supplemental inorganic nutrients to the filter bed (Coleman et al. 1995).

The pH of the biofilter medium directly affects the micro-organisms and microbial enzymes that metabolize odour compounds, and might also influence the availability of required nutrients (Atlas and Bartha 1993). Near-neutral pH is ideal (Devinny et al. 1999; Yang and Allen 1994; Leson and Winer 1991). The pH in biofilters associated with animal facilities may decrease over prolonged periods because of the nitrification of ammonia and the oxidation of hydrogen sulphide (Atlas and Bartha 1993). Buffer compounds can be added to the filter medium to prevent acidification, or prescrubbers may be used to remove the offending compounds (Le Cloirec 2001; Dong et al. 1997; Amirhor and Gould 1997; Scholtens et al. 1991). Recent research indicates that in some circumstances a flow of leachate may be required in order to flush accumulated acids from the filter bed (Abolghasemi 2003).

Exhaust air streams from poultry units are often carry a substantial amount of dust, which can compromise the effectiveness of a biofilter by clogging the pore spaces. Dust filtration of the air stream, therefore, is recommended for poultry units, but usually is unnecessary for most swine or dairy operations (Nicolai and Janni 1999).

10.3 Design

Factors to consider when designing biofilters are outlined below. For a detailed design procedure, refer to the Extension Program of the Department of Biosystems and Agricultural Engineering, University of Minnesota. This agency has published information and procedures for designing an on-ground, open-bed biofilter intended for use with a livestock facility, based on estimated ventilation requirements and the properties of available filter materials (Nicolai 1998). Swanson and Loehr (1997) have also published a general guide to understanding biofilter applications and design.

The most popular and inexpensive style of biofilter for treating exhaust air from livestock facilities is an in-ground or on-ground, open-bed filter of compost and wood chips (Janni and Nicolai 2000). Such a filter may be situated in a lined earthen berm, an open concrete tank, or may simply be composed of filter medium piled over a plenum formed by shipping pallets laid on the ground. Exhaust air from a mechanically ventilated animal housing unit is forced into a plenum under the filter bed and moves upward through the filter medium. The airflow should be evenly distributed across the filter bed.

A good filter medium must provide optimum conditions for the growth of a large, diverse microbial population (Burrowes et al. 2001). Biofilter media must provide microbial colonization sites, retain moisture, supply inorganic nutrients, buffer pH, and help maintain a mesothermic temperature range. The characteristics of the filter medium should also include physical stability and good bearing strength, so that it will degrade slowly, yield relatively clear leachate, and compact little with time. It should also be very porous so that the pressure drop is low and the required airflow is relatively unhindered. Pressure drops for typical filter media and airflow ranges for compost/wood chip mixtures range from 10 Pa/m at 5 L/s/m^2 for a mixture with 40% void volume, to 500 Pa/m at 3300 L/s/m^2 for a mixture with 60% void volume (Nicolai and Janni 2001). Some empirical equations are available for estimating the pressure drop across beds of granular materials based on measured values such as particle size, bulk density, and particle density (ASAE 2000).

Compost is a popular filter material, with an operating life of about 2 to 5 years (Burrowes et al. 2001). Compost hosts high concentrations of micro-organisms, has large particulate surface areas, high permeability, good water retention, and good pH buffering capacity. Drawbacks of compost include odour emissions from unaerated or immature compost. If the bearing capacity of the compost is low, then compaction of the filter bed can result in short-circuiting. Varying moisture content can shrink and swell a compost biofilter bed and result in cracking and crusting, although stirring every few months reduces this problem (Burrowes et al. 2001). Finally, very dry compost is hydrophobic and adding moisture may require working the entire bed (Burrowes et al. 2001).

Soil is more physically and chemically stable than compost, and is also an excellent pH buffer. Soil usually has good bearing strength, which precludes much compaction of the filter bed. The operating life of a biofilter with a soil medium has been shown to be more than 10 years in Europe and more than 30 years in Washington State (Burrowes et al. 2001). The permeability of some native soils, however, is low, resulting in high pressure drops and low allowable surface loading rates. Sandy loams are generally more suitable for biofiltration (Burrowes et al. 2001; Nicolai and Janni 1998). Another drawback of soils is that they are often more difficult than compost to keep out of the air distribution system or to amend, should the need arise.

Chipped wood or bark provides high structural stability and bearing strength, and good porosity. These materials are a moderate source of nutrients and may retain some moisture. These properties depend on the particle size and to some extent on the type of wood used. The primary role of wood products in a biofilter is to maintain the porosity and structure of the filter bed, although blending bark with compost enhances many of the favourable characteristics of the latter (Burrowes et al. 2001).

A biofilter should be sized based on the volumetric airflow rate that must be treated. The quantity of filter medium must be such that the treated air stream is in contact with the biofilter medium for long enough to allow the absorption and metabolism of the odorous compounds. Sizing of a filter for a given airflow is therefore based on an appropriate empty bed contact time (EBCT) (Janni and Nicolai 1997). Five seconds EBCT is recommended for swine and dairy operation, 3 s for poultry, and 10 s for covered manure storage systems. These EBCT values result in about an 80% reduction in emissions in a properly maintained biofilter (Nicolai and Janni (1999) and Nicolai et al. 1999). Filter thickness should be at least 250 to 450 mm (10 to 18 in.) (Janni 2000). Increasing the depth gives a smaller area for a given volume of filter medium, but also increases the possibility of compaction of the filter medium and a resulting restriction in airflow and loss of odour removal efficiency. A typical footprint is about 10 to 17 m^2/(1000 L/s) (50 to 85 ft^2/1000 cfm) (Schmidt et al. 2000; Janni 2000).

Moisture from the biofilter bed is lost through evaporation and must be replaced either by moisture from the inlet air stream, precipitation, or irrigation. Applicable water application apparatus include surface irrigators, soaker hoses, and prehumidifiers. Surface irrigation is suitable to environments where evapotranspiration rates are high, but the surface of the biofilter must be frequently irrigated at low application rates to prevent settling, compaction, and saturation of the medium. Impact sprinklers are often used for this purpose because fine mist sprayers are prone to plugging (Burrowes et al. 2001). Surface irrigation alone, however, is not recommended because of the tendency to wet only the top of the filter bed, whereas most drying in upflow filters occurs from the bottom up (Burrowes et al. 2001). Soaker hoses can be located in the middle of the filter bed to provide supplemental moisture. The inlet air can also be prehumidified by placing spray nozzles in the inlet air ducts, or using spray chambers or packed tower scrubbers (Lannon 2000). With the use of timers, controllers, and moisture sensors, an effective automated control system can be devised.

An on-ground or in-ground, open-bed biofilter must be sloped or located on a well-drained site to prevent the accumulation or water in plenum (Nicolai 1998). Leachate from a biofilter might be acidic if inorganic compounds in the air stream are being degraded, and it might be necessary to contain and treat it to prevent groundwater contamination (Burrowes et al. 2001). Plastic liners can be used for this purpose in conjunction with a drainage pipe sized for the maximum expected storm load (e.g. 100-year storm) (Burrowes et al. 2001). The drainage system must also be able to handle the water flow from a broken soaker hose or possible other malfunction (Burrowes et al. 2001). In more advanced systems, the drainage water might be recirculated to maintain the moisture and nutrient content of the filter bed (Swanson and Loehr 1997; Abolghasemi 2003).

10.4 Operation and Maintenance

The appropriate operating conditions for good microbial growth take time to stabilize in a new biofilter. During the start-up of a new biofilter, there is usually an *acclimation* period of up to several weeks in which the odour removal efficiencies start low and gradually improve (Nicolai 1998). Once established, however, microbial activity is usually sustained with minimal inputs except an appropriate waste air stream. The maintenance of a proper moisture regime is, however, vital to the effective operation of the biofilter (Striebig et al. 2001). As well, excess vegetation should be removed, and noxious weeds and rodent infestations must be controlled.

Due to the accumulation of microbial biomass, the odour removal effectiveness of biofilter medium may decrease with time (Alonso et al. 1997). In the compost or soil biofilters commonly used in agriculture, there is no convenient way of removing this excess biomass from the filter medium short of reworking or replacing the entire filter bed (Sadowsky et al. 1999). Such biofilters are considered to have an effective operating life of about three to five years (Schmidt et al. 2000).

When the medium from a compost or soil biofilter is replaced, the old medium may be screened to remove any bulking agents (e.g., wood chips) for reuse, and then land applied. Over the life span of the filter, however, nitrogen and sulphur are sequestered in the filter as ammonia and hydrogen sulphide are removed from the waste air stream. Since only a limited amount of research has been done to quantify the nutrients that are sequestered (Sun et al. 2000), nutrient analysis is advisable when first deciding whether not to apply the material on land.

10.5 Centres of Research

Biofiltration has been used in the European livestock industry for decades (Nielsen 1986). Biofiltration is a current practice in the agricultural sector of many European countries, and research in biofilter use is ongoing in a number of these including: Poland (Eymont et al. 2000), France (Guingand and Granier 1996), and Hungary (Meszaros 1994; Meszaros et al. 1994). Biofiltration has been used for odour control in German livestock production facilities since the early 1980s and is still a very active area of research there (Martinec and Hartung 2001; Martinec et al. 2001, 2000a, 2000b, 2000c; Martens et al. 2001, 1999; Hahne and Vorlop 2001; Hahne et al. 1998; Harder and Grimm 1997; Siemers 1997, 1996; Hopp and Hugle 1996; Zeisig 1988). Currently, permeable covers of biological material are used extensively in the Netherlands to reduce ammonia emissions from manure storage units (Jacobson et al. 1998), and open-bed biofilters for treating emissions from animal housing are also being investigated (Scholtens 1991; Scholtens et al. 1987). As well, TNO Institute of Environmental Sciences, the Netherlands, is one center where research on fungal biofiltration is taking place (von Groenestijn et al. 2001). The Silsoe Research Station in Reading, UK, is also an active center of research in this area (Pearson 1990, 1988; Pearson et al. 1995, 1992). There is undoubtedly research activity currently proceeding in other European countries as well that has not been extensively reported in the English-language literature.

The Department of Biosystems Engineering at the University of Manitoba has an active program investigating the use of biofilters in the cold temperatures typical of Canadian conditions (Mann et al. 2002; De Bruyn et al. 2001, 2000). This research has included the retrofit of commercial swine production facilities with low-cost biofilters using compost and wood chips.

Research at the Department of Agriculture, Food and Nutritional Science of the University of Alberta uses closed-bed, pilot-scale biofilters to investigate the effect of various operating parameters on odour removal efficiency. In these studies, NH_3 and H_2S played a major role in the biofiltration process due to their by-products' toxicity and their effect on pH. The following experiments were carried out to evaluate the effects of these gases on the biofiltration process from swine facility exhaust air.

a. **Preliminary experiments**

   Materials such as coarse peat moss, ground polystyrene, woodchips, mixed peat moss and polystyrene, perlite, expanded polystyrene, coarse compost were used as media for the biofilters. Coarse compost materials were found to work better for uniform water application and providing optimum moisture content for the media.

b. **Dilute sulphuric acid solution (0.02%) in a bioscrubber**

   The average NH_3 concentration was 21 ppm with a standard deviation of 5.2 ppm while the average of H_2S concentration was 3 ppm with a standard deviation 1.6 ppm. A bioscrubber was used to pretreat the exhaust air prior to biofiltration. Using a bioscrubber with a sulphuric acid solution, resulting in an average pH of 6.5, reduced ammonia by 82%, H_2S by 75%, and odour by 58%. A bioscrubber without sulphuric acid (resulting in an average pH of 7.05) reduced ammonia by 60%, H_2S by 52%, and odour by 58%. The maximum odour reduction rate of 68% for both biofilters occurred when the sulphate concentration was 11,000 ppm in the bioscrubbers using acid and 1,800 ppm in the bioscrubber without the addition of acid.

c. **Effect of ammonia on biofiltration**

   These experiments took place with three replications and four treatments (0, 20, 40, 80 ppm NH_3). Four biofilters and a bioscrubber were used. The bioscrubber contained polystyrene pieces (12.5 mm) and had an empty bed retention time (EBRT) of 4 s. Tables 2 and 3 summarize some of the results.

   i. **Bioscrubber performance:** Bioscrubber exhaust air pumped to the biofilter was normally 100% RH. The odour was reduced by 61% during the three trials. The overall NH_3 concentration in the barn (10 ppm) was reduced by 92.5±3.33%.

   ii. **Biofilter performance:** Water application to the biofilter was found to be a critical parameter for two reasons: a) providing optimum moisture content to the biofilter media, and b) transporting nutrients and reducing toxicity of the metabolic by-products such as nitrite.

Table 2. Overall mean nitrite and nitrate production:

Materials produced	No ammonia injection	20 ppm ammonia injection	40 ppm ammonia injection	80 ppm ammonia injection
Total NO_2-N g/m³/d	1.6±0.19	33.8±3.89	36.2±2.89	29.0±4
Total NO_3-N g/m³/d	4.7±0.63	9.7±1.2	2.3±0.28	0.2±0.11

Table 3. Overall average of elimination capacity, pH values and amount of leachate:

Factor	No ammonia injection	20 ppm ammonia injection	40 ppm ammonia injection	80 ppm ammonia injection
Elimination capacity g/m³/h	0.6±0.39	5.2±0.39	8.5±0.39	12.0±0.39
pH	7.5±0.04	8.0±0.04	8.3±0.04	8.6±0.04
Leachate L/m³/d	13.5±0.4	18.0±0.45	20.0±0.4	20.7±0.4

The highest values of NO_2-N and NO_3-N were produced in biofilter injected with 20 ppm. No NO_3-N was produced in the biofilter injected with 80 ppm NH_3. As the concentration of nitrite and nitrate increases, the amount of applied water must increase to maintain an optimum level of total dissolved solids (4000 ppm). Overall, olfactometrytest results showed that the bioscrubber initially reduced the odour concentration by 61%. Then, the first biofilter (without ammonia injection) further reduced odour by an average of 25%; the second biofilter (20 ppm) increased odour levels by 5%; the third biofilter (40 ppm) increased odours by 2%; and the last biofilter (80 ppm) increased odours by 29%.

Some work is also being done on the partitioning of airspace in swine buildings to reduce the volume of exhaust air that must be filtered to reduce odour emissions (Feddes et al. 2001; Lemay et al. 2000). This work is also an example of a cooperative project in which the Alberta Research Council has engaged university and industry interests in biofilter technology. The provincial Department of Agriculture, Food and Rural Development is investigating biofiltration as part of its Odour Control Initiative.

The Animal and Poultry Waste Management Center (APWMC) is a collaboration of North Carolina State University, 20 other universities in the region, and other stakeholder groups (Williams 2001). Projects include the demonstration of technologies on a pilot scale and at commercial swine facilities. These projects include the use of biofiltration in the swine industry, which is a major player in the North Carolina economy (Classen et al. 2000; Swine Odor Task Force 1998).

The Extension Program of the Department of Biosystems and Agricultural Engineering, University of Minnesota, has developed design procedures and tested low-cost biofilters for use in the livestock industry. Their testing and design information is specifically for the cold-weather climate of Minnesota, and is therefore also relevant to swine production operations in Canada. The biofilters are meant to be simple in design and inexpensive to build and maintain. Specifications include highly permeable media (low pressure drop and fan costs), no dust filtration, surface irrigation of filter bed with no prehumidification, and no walls or covers. The Extension Service tests its concepts with an open-bed, wood chip and compost biofilter at a 700-sow production facility (Nicolai and Janni 1999). Clanton et al. (1997) are also working with organic floating covers.

In research at the Department of Agricultural and Biosystems Engineering, Iowa State University, organic floating covers are being examined for use as biofilters on open manure storage systems (Zhang et al. 1999; Bundy et al. 1997). Open-bed biofiltration is being compared with other odour-control techniques

(Bottcher et al. 2000). Research by private industry into the nature and control of agricultural odours is also ongoing (Eaton 1996).

10.6 Concluding Comments

a. The open-bed design is common in agricultural operations because it is relatively inexpensive to construct and maintain.

b. Compost and wood chips are inexpensive, locally available and effective filter media in most Canadian settings.

c. Open-bed biofilters with compost filter media can attain odour removal efficiencies of between 75 and 90%.

d. When a biofilter is fully operational it requires minimal maintenance. Proper moisture is critical. Some pest and weed control measures may also be necessary. In a compost biofilter, clogging by bacterial biomass or dust may make replacement of the medium necessary after 3 to 5 years.

e. Biofilters should be integrated into the original facility design for maximum economy of construction (Zhang et al. 2002). For instance, a biofilter added after construction requires additional fans to supplement existing exhaust fans.

f. Cold weather does not seem to inhibit the operation of industrial scale, open-bed biofilters. They appear to be an effective method for reducing odour emissions from livestock facilities even in the climatic extremes of the Canadian Prairies.

g. Effective means of managing moisture in the biofilter must be investigated, especially when treating high flow rates of unsaturated inlet air in dry conditions. In upflow biofilters, drying occurs from the bottom of the filter bed whereas moisture is most easily applied from the top. Prehumidification systems, embedded hoses, or downflow biofiltration might be useful design options.

h. High ammonia concentrations can compromise microbial growth in a biofilter. Scrubbing the inlet air with a water or acid bath might be necessary. A limited flow of leachate may help to purge accumulated acids from the filter material.

i. Recirculation of leachate may help to maintain nutrient concentrations in the filter bed.

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