Ammonia and Hydrogen Sulfide Emissions from Livestock Production

Atta Atia, Karen Haugen-Kozyra and Mohamed Amrani
Alberta Agriculture,
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Science to Social Issues

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A Ammonia Emissions From Livestock Production

A.1 Introduction

The aim of this study is to review the currently available information, knowledge and technology regarding ammonia emissions from livestock production, manure storage facilities and emissions due to manure application to soils.

At atmospheric pressure, ammonia (NH_3) is a colourless gas, which is lighter than air and possesses a strong, penetrating odour. Ammonia dissolves readily in water, where it ionizes to form an ammonium ion. The solubility of ammonia in water is influenced by the atmospheric pressure, temperature, and by dissolved or suspended materials.

Livestock production is a major contributor of ammonia emissions (ApSimon et al. 1987; Allen et al. 1988; Koerkamp et al. 1998; Hobbs et al. 1999; Aneja et al. 2000; Battye et al. 1994; Kurvits and Marata 1998; Sommer and Hutchings 1995). Ammonia is produced inside livestock buildings, in open feedlots, in manure storage facilities, during manure handling and treatment and when manure is applied to soils. Koerkamp et al. (1998) reported that ammonia is usually generated from manure and animal waste according to the following reactions.

Aerobic decomposition of uric acid:

$$C_5H_4O_3N_4 + 1.5O_2 + 4H_2O \longrightarrow 5CO_2 + 4NH_3$$

Urea hydrolysis:

$$CO(NH_2)_2 + H_2O \longrightarrow CO_2 + 2NH_3$$

Mineralization:

$$\text{undigested protein (bacterial degradation)} \longrightarrow NH_3$$

Oliver et al. (1998) estimated the total annual global ammonia emissions at 54 Mtonnes NH_3-N. Globally, livestock production is responsible for about 50% of ammonia emissions (Table 1).

According to McCrory and Hobbs (2001) livestock production has been identified as a primary contributor to ammonia in Europe (80%). Agriculture, Nature Management and Fisheries (1995) reported that livestock production in the Netherlands accounts for 55% of all ammonia emissions from agriculture. The land spreading of cattle manure has been identified as the single largest source of NH_3 emissions, accounting for 45 Ktonne of the 226 ktonne NH_3-N arising annually from agricultural sources in the U.K. (Misselbrook et al. 2000). Approximately 80% of ammonia in the United States comes from agricultural sources (Battye 1994). Kurvits and Marta (1998) reported that the total annual ammonia in Canada is 569 Ktonne NH_3-N; 87% was attributed to agricultural activities. Livestock production is responsible for 82% of total agricultural ammonia emissions in Canada (Table 2).

In Alberta, agriculture produces 90% of the total ammonia emissions (Chetner and Sasaki, 2001). A total of 120,717 tonnes of ammonia was emitted by livestock production in the year 2000, which accounted for 71% of agriculturally produced

Table 1. Global sources of ammonia from domestic animals Source: Asman 1992.

Source	Ammonia Emissions (10^6 tonnes Nitrogen yr^{-1})	%
Dairy cattle	4.3	8
Non-dairy cattle	8.6	16
Buffalo	1.2	2
Swine	3.4	6
Poultry	1.9	4
Sheep/Goats	1.5	3
Other animals	0.7	1
Total	21.6	40

Table 2. Trends in Canadian livestock ammonia emissions (NH_3-N) in tonnes per year Source: Kurvits and Marta 1998.

Source	1990 Ammonia Emissions (10^3 tonnes Nitrogen)	1995 Ammonia Emissions (10^6 tonnes Nitrogen)	1990-1995 (%) change
Cattle	257.38	331.01	+28
Swine	92.43	106.82	+15
Poultry	107.39	118.59	+10
Sheep	2.47	2.49	+1
Horses	4.35	4.38	+1
Fur farms	0.28	0.28	0
Total	**464.3**	**563.58**	**+21**

ammonia emissions in Alberta (Chetner and Sasaki 2001). Cattle operations contributed 79% of ammonia emissions from livestock in Alberta (Chetner and Sasaki 2001).

A.2 Ammonia Fate, Deposition and Transport

Deposition of ammonia from the atmosphere to land and water is affected by several environmental factors, such as temperature, wind speed, radiation, moisture, atmospheric stability, physical and chemical properties of gases, and surface conditions. Thomas et al. (2002) reported that ammonia has a short atmospheric lifetime (hours to days) because of the multi-phase chemistry (gas-solid and aqueous solution). Arogo et al. (2001) cited Krause-Plass et al. (1993) who explained that the transportation of volatilized NH_3 over long distances depends on the competition between upward diffusion and transformation to NH_4^+ aerosols, and surface deposition. Asman (1998) showed that the amount of ammonia dry deposition at a certain distance from the source depends on the source height. Apsimon and Kruse-Plass (1991) reported that ammonia can be transported over long distances, but Asman (1998) developed a model that predicts that up to 60% of NH_3 could be deposited at a distance of 1.6 km from the emissions source. Ferm (1998) reported that 50% of emitted ammonia is deposited 50 km from the source of emissions. However, if the atmospheric NH_3 reacts with gases in the atmosphere to form sub-micrometer diameter particles, then the NH_3 is deposited much more slowly, leading to a transport distance of 100s to 1000s of kilometres.

Apsimon et al. (1987) reported that 50% of nationally emitted ammonia in Ireland is deposited within the country. Ferm (1998) also reported that in Europe, generally 50% of ammonia emissions are deposited within the country of origin.

Ammonia is a weak base. As a base, the physical and chemical characteristics of ammonia are pH dependent and so the environmental fate of ammonia is also pH dependent. Schnoor et al. (2001) reported that NH_3 reacts with water to form ammonium and hydroxide ions in air inside livestock buildings or around feedlots. When water is evaporated from the air, ammonium sulfate will be formed. The presence of ammonium sulfate in the air is an important mitigation impact for ammonia because particles can stay in the air for several days and cause decreased visibility (EPA 2000). Ammonia reacts with nitric acid to form ammonium nitrate. This reaction is reversible (e.g., the ammonium nitrate can easily evaporate), and the formation direction is favored by low temperature and a high relative humidity. As a result, the concentrations of ammonium nitrate are often higher during the nighttime or during colder periods of the year.

Modeling is used extensively to estimate the transport and deposition of air pollutants. In Europe, the EUTREND model is used to assess specific ammonia-ammonium dry deposition. This model was mainly developed to calculate concentration, dispersion and deposition of NH_3 and other pollutants. The Regional Acid Deposition Model (RADM) has been modified to include NH_3. This model is based on episodic meteorological data to calculate transport, transformation rate and deposition of pollutants such as ammonia. RADM is used mainly in the eastern half of the United States. A Canadian study by Zhang et al. (1999) developed a Routine Deposition Model (RDM) for pollutants dry deposition. Another Canadian study (Moran et al. 2002) resulted in the development of the AURAMS regional air quality system to calculate transport patterns and deposition of air pollutants, including ammonia.

Aneja et al. (2000) found that ammonia fluxes varied seasonally, ranging from an average of 305 (February) to 4,017 (August) Pico g N/m^2/minute. Stowell et al. (2002) collected air samples from the exhaust produced from a 960 head, High-rise TM swine finishing facility and a nearby 1000 head, tunnel-ventilated, deep-pit finishing facility during 4 finishing cycles from 1999-2001. They found cold outdoor temperatures generally resulted in higher ammonia concentrations in exhaust air.

A.3 Health and Environmental Impacts Due to Ammonia Emissions from Manure

The current United States Occupational Safety and Health Administration (OSHA) Threshold Level Volume (TLV) for ammonia is 25 ppm with a short-term exposure limit of 35 ppm. An exposure to 300 to 500 ppm for 30 to 60 minutes might be hazardous to health (ATSDR, 1990). Arogo et al. (2001) listed the consequences of exceeding the threshold levels of ammonia as:

1. Ammonia reacts with sulfur dioxide and nitrous oxides in the atmosphere to form particulate matter with a mass median diameter of 2.5 microns (PM-2.5). Particulates can cause respiratory problems in humans and animals, either directly or by carrying pathogens, endotoxins, or allergens;
2. Nitrate contamination of drinking water;
3. Eutrophication of surface water bodies resulting in harmful algal blooms and decreased water quality;
4. Vegetation or ecosystem changes due to higher concentrations of N;
5. Climatic changes associated with increases in nitrous oxide (NO_2);
6. N saturation of forest soils; and
7. Soil acidification via nitrification and leaching.

High concentrations (above recommended thresholds) of NH_3 inside animal confinement buildings pose serious potential hazards to humans and animals (Reece et al. 1980; Carr et al. 1990; Crook et al. 1991). In poultry housing, birds exposed to high levels of ammonia showed reductions in feed consumption, feed efficiency, live weight gain and egg production (Charles and Payne 1966; Quarles and Kling 1974; Reece and Lott 1980; Xin et al. 1987). Ammonia may be converted to nitric acid after atmospheric deposition and microbial conversion in the soil, making a significant contribution to total acid deposition in the soils. This leads to acidification and eutrophication of sensitive habitat, with consequent changes in fauna and flora communities. Ammonia can be returned in precipitation and, together with NO_2 in dry deposition, add to the soil mineral nitrogen fraction (Goss et al. 1994). The deposition of ammonia in forest soils decreases the natural capability of these soils to take up methane (CH_4), thus increasing the concentration of greenhouse gases in the atmosphere. Also, the disposition of ammonia in forests will lead to alteration of growth and development of forest plants (Kurvits and Marta 1998; Pitcairn et al. 1998). Ammonia in the atmosphere reacts with acid gases to form fine aerosols (Harris et al. 2001; Aneja et al. 2000). Agriculture and Agri-Food Canada (AAFC 1998) reported that in the eastern Fraser Valley of British Columbia, aerosols of ammonium nitrate and ammonium sulfate were measured to be up to 70% of the fine particulates during the summer, resulting in visibility impairment. Kurvets and Marta (1998) cited Vitousek et al. (1997), who found the effects of increased deposition of nitrogen compounds in Canada include: increased regional concentration of oxide nitrogen, substantial acidification of soils and waters in many regions, generally increased transport of nitrogen by rivers into estuaries and coastal water, and accelerated losses of biological diversity. Yale Center for Environmental Law and Policy (2002) cited Rudek (1997) who reported that there is a concern that the abundance of ammonia from swine facilities is also contributing to the over-fertilization of nitrogen-sensitive prairies, resulting in the proliferation of weedy species at the expense of native plants.

A.4 Ammonia Measurement Techniques

Lim et al. (2002) reported that measurements of gases, including ammonia at livestock buildings with different manure management systems, would enhance the validation and use of setback guidelines and atmospheric dispersion models. Phillips et al. (2001) reported that the ability to measure ammonia emissions is critical to their quantification, and wide ranges of techniques are available. However, a standardized method for measuring ammonia emissions is lacking. Each of these techniques varies in its sensitivity, selectivity, speed and cost. Measuring ammonia is expensive, extensive and time consuming (Aneja 1997; Harper and Sharpe 1998).

Measurement techniques for ammonia include:

1. Passive diffusion device (Van't Klooster et al. 1996; Sommer et al. 1996; Philips et al. 2000; Welch et al. 2001; Flint et al. 2000).
2. Dynamic chamber techniques (Aneja et al. 2000, 2001).
3. Chemiluminescence NO_2 analyzers (Philips et al. 1998).
4. Mass balance techniques.
5. Packed bed detector tubes (Sweeten et al. 1991).
6. Continuous flow denuders (Mennen et al. 1996).

Arogo et al. (2001) extensively reviewed all ammonia measurement techniques, how they work, their cost and reliability. They also reported on the most common methods to calculate the exchange rate of NH_3 between a source and the atmosphere. These methods included: mass balance; meteorological; aerodynamic; Bowen ratio; and chambers and wind tunnel methods. The most commonly used methods for measuring ammonia in the U.K. are the micrometeorological and mass balance methods, which employ passive flux samplers, a system of small wind tunnels suitable for small-plot studies, and the equilibrium concentration technique, employing a system of small dynamic chambers. Berckmans et al. (1992) in Belgium developed a thick film semi-conducting metal oxide sensor for monitoring ammonia concentrations within, and from, livestock confinement buildings. Fourier Transform Infrared (FTIR) has recently been used to measure ammonia concentration. The concentration of ammonia measured by this method can be used with micro-micrometeorological data to determine point and aerial ammonia emissions. Aneja et al. (2000) used a flux chamber method to measure NH_3 from lagoon surfaces. They reported that NH_3 measured by this method reflected a diurnal variation, which is highly correlated with lagoon surface water temperature.

A.5 Ammonia Emissions Factors and Rates from Livestock Facilities

Arogo et al. (2001) reported that many factors determine ammonia emissions rates from livestock facilities. These factors are:

1. The number, type and age/weight of animals.
2. Housing design and management.
3. Type of manure storage and treatment.
4. Land application techniques.
5. N excretion rates per animals.
6. Manure pH (Aarnink et al. 1993; Freney et al. 1983; Hoeksma et al. 1993; Kroodsma et al. 1994; Svensson 1993).

Anderson et al. (1996) reported that ammonia emissions rates were found to be correlated or slightly correlated with the pH values of the manure samples he collected for his bedding studies. They reported that the use of peat in straw bedding has been shown to reduce the release of ammonia due to a lowered pH value of the manure. Environmental factors, especially temperature (Aarnink et al. 1993; Anderson 1995; Beauchamp et al. 1978; Emerson et al. 1975; Frenay et al. 1983; Hoeksma et al. 1993; Sommer et al. 1991; Wilhelm et al. 1999), and overall ventilation rate (Anderson 1995; Gustafsson 1997) are the major factors in controlling manure ammonia gas levels within livestock confinement buildings. The rate of emission also depends on the wind speed (Denmead et al.1982). Emissions rates of ammonia from livestock are expressed as the mass of ammonia per unit time and by animal live weight or animal unit. Sometimes ammonia emissions could be expressed as mass of ammonia per unit area. The general approach for estimating the contribution of livestock sources for ammonia emissions is to construct appropriate emissions factors, which are linked to source parameters that are known or can be easily obtained. There is no standard method for reporting ammonia emissions factors, making it harder for comparison studies. Arogo and Westerman (2002) recommended that the only way to determine accurate emissions factors is through measurement. Therefore, measurements should be done: for all the different livestock categories (e.g. by weight and building types); from associated manure storage/treatment systems; and land application/utilization methods. They also recommended that measurements should be done for all geographical regions and livestock feeding operation characteristics. Measurements or monitoring ammonia emissions from livestock feeding operations should be done continuously over long periods of time, preferably for one year to cover all weather seasons.

Comprehensive studies have been conducted by several researchers to estimate ammonia emissions factors from different livestock buildings in Europe (Aarnink et al.1997; Hendriks et al. 1998; Groot KoerKamp et al. 1998; Demmers et al. 1999; Asman 1992). Asman (1992) grouped animals into 21 categories and sub-categories, and three broad manure management practices. Van der Hoek (1994) reported that Asman's determination of livestock emissions factors did not consider the animal weight and seasonal variation of the climate. But Asman's emissions factors are still widely used in the United States and Canada due to the fact that no other reliable data are available to determine the NH_3 emissions factors. An emissions factor developed for one species of animal could be translated to another species of animal by adjusting the difference in the excretion rate. Groot KoerKamp et al. (1998) summarized ammonia emissions data for different livestock and housing systems in England, Denmark, the Netherlands and Germany. The comparison of the data reveals a variation in the mean emissions value for each animal category for the different countries.

Arogo and Westerman (2002) emphasized that once the emissions factors are developed, substantial judgment is still necessary in selecting and using emissions factors to develop NH_3 inventories for a region, or estimating NH_3 emissions from a facility. They stressed the importance of evaluating the assumptions and techniques that were used to develop the emissions factors to determine their suitability to the conditions or region for which the inventory is being developed. Arogo et al. (2001) summarized ammonia emissions from swine, cattle and poultry production (Tables 3, 4 and 5). In Alberta, Chetner and Sasaki (2001) used emissions factors developed by various groups, such as the United States Department of Agriculture Agricultural Air Quality Task Force, Environment Canada, some air emissions studies in Alberta, United States Environmental Protection Agency and emissions factors derived from emissions inventories in Alberta. They used the emissions factors to calculate total ammonia from livestock operations for 11 airshed areas in Alberta (Table 6).

A.6 Odours and Ammonia

Research to determine the relationship between ammonia concentration and odour has produced varied results. Schutle et al. (1985) found that there was a link between high levels of ammonia emissions and odour, but Liu et al. (1993) reported that levels of ammonia emissions are not a good indicator of the odour threshold from swine manure. Nicolai (1995) showed that the relationship between ammonia and odour from storage units cannot always be correlated. There are other small amounts of volatile compounds, which can also influence odour. Jacboson (2002) cited DeBode (1991) who studied the relationship between odour intensity and ammonia concentration.
He found that by covering manure storage units, ammonia emissions were reduced from 75% to 100% while odour intensity was reduced from 28% to 72%.

Table 3. Ammonia emissions (NH_3) from swine production *Source: Arogo et al. 2001.*

Livestock	Flooring type	Low average (mg/AU-h)	High average (mg/AU-h)	Reference
Sows	Litter	744	3248	GrootKamp et al. 1998
Sows	Slats	1049	1701	GrootKamp et al. 1998
Nursery pigs	Slats	649	1526	GrootKamp et al. 1998
Finishing pigs	Litter	1429	375	GrootKamp et al. 1998
Finishing pigs	Slats	2076	2592	GrootKamp et al. 1998
Finishing pigs	-	2710	6130	Heber et al. 2000
Finishing pigs	-		3000	Hinz and Linke 1998
Grow/Finishing	Slats		6020	Ni et al. 2000b
Grow/Finishing		2000	3600	Hendriks et al. 1998

Table 4. Ammonia emissions from cattle production Source: Arogo et al. 2001.

Livestock	Flooring type	Average (mg/AU-h)	Reference
Beef	Straw	0.34	Demmers et al. 2001
Beef	Straw	0.81	Demmers et al. 1998
Beef	Litter	0.43-0.48	Koerkamp et al. 1998
Beef	Slats	0.37-0.9	Koerkamp et al. 1998
Calves	Litter	0.32-1.04	Koerkamp et al. 1998
Calves	SF	1.15-1.80	Koerkamp et al. 1998
Dairy	Litter	0.26-0.89	Koerkamp et al. 1998
Dairy	Straw	1.02	Demmers et al. 2001
Dairy	FSF	0.95	Van't Klooster 1994
Dairy	Cubicles	0.84-1.77	Koerkamp et al. 1998
Dairy		0.14	Phillips et al. 1998
Dairy	Straw	0.25	Phillips et al. 1998
Dairy	Slat	31-48.6 g NH_3/d/cow	Kroodsma et al. 1993
Dairy	Straw	1.32	Demmers et al. 1998

Table 5. Ammonia emissions from poultry production Source: Arogo et al. 2001.

Poultry type	House/Manure system	NH_3 conc. (ppm)	NH_3 emissions rate (g NH_3/h-AU)	Reference
Broiler	Litter	24.2	9.2	Wathes et al. 1997
Layers	Battery cage/Deep pit	13.5	9.2	Wathes et al. 1997
Layers	Perchery/Deep pit	12.3	9.2	Wathes et al. 1997
Layers	Perchery		8-10	Phillips et al. 1995
Layers	Battery cage		7-12.3	Phillips et al. 1995
Broiler	Litter		8.5-9.3	Phillips et al. 1995
Broiler	Litter		0.6-8.1	Amon et al. 1997
Broiler	Litter	8-27.1	2.2-8.3	Koerkamp et al. 1998
Broiler	Litter		5.4	Demers et al. 1999
Layers	Battery cage	1.6-11.9	0.6-9.3	Koerkamp et al. 1998
Layers	Perchery/Litter	8.3-29.6	7.3-10.9	Koerkamp et al. 1998
Layers	Liquid manure		4.4	Hartung and Phillips 1994
Layers	Litter		2.0	Hartung and Phillips 1994

Table 6. Alberta livestock ammonia emissions in tonnes per year in 2000 Source: Chetner and Sasaki 2001.

Airshed Name	Cattle	Swine	Sheep	Poultry	Horses	Other	Total
Athabasca and Cold Lake Region	8435	1038	103	511	194	41	10322
Calgary	3373	301	59	328	230	48	4339
Drumheller Region	15183	1857	97	754	423	53	18367
Edmonton Region	12452	1978	115	1223	476	245	16489
Northwest Region	825	77	11	7	39	7	966
Parkland Zone	13167	3300	155	759	574	91	18047
Grande Prairie and Peace River Region	6473	735	302	179	227	57	7972
Southern Alberta Region	23490	3818	315	803	490	95	29011
South Wood Buffalo Region	370	115	11	1	14	1	512
Wainwright Lloydminster Region	8156	1199	54	203	182	24	9818
West Central Zone	3798	261	37	333	375	69	4872
Provincial Total	95722	14679	1258	5103	3224	731	120717

Both odour intensity and gas emissions were reduced, but in significantly different amounts. For more information see the odour and air quality part of this report.

A.7 Ammonia Emissions Control Strategies

Arogo et al. (2001) reported that strategies for reducing NH_3 emissions from livestock buildings and manure storage facilities should be directed towards reducing:

1. NH_3 formation;
2. NH_3 losses immediately after it has been formed; or
3. The NH_3 loss potential.

Choosing the appropriate measure or technology for reducing ammonia emissions depends on many factors. The type of manure and manure storage systems and cost consideration are the two most important factors. The technical and economical feasibilities of different types of ammonia reduction practices and technologies are reviewed and evaluated here.

Performance evaluations of emissions abatement strategies often cite poorly understood microbiological processes or other poorly defined intrinsic properties of swine manure management systems as the reason for ineffective performance of a particular emissions abatement method (Miner 1995). Cost is the driving factor behind the adoption of ammonia emissions control technologies. Sometimes, using some technologies to reduce the ammonia emissions might lead to unwanted results. For example, acidification of manure to reduce emissions of ammonia will result in an increase in hydrogen sulfide emissions. The ammonia emissions control techniques in this paper are divided into three main categories: suppression methods, inhibition methods, and capture and control methods. Each category includes different ammonia emissions control techniques.

A.7.1 Suppression Methods

A.7.1.1 Manure storage covers

Ammonia losses are much higher from manure stored in open tanks and lagoons than covered tanks or lagoons (Bussink and Onema 1998; Hornig et al. 1999). Small and Danish (1999) reported that approximately 30 to 50% of the total nitrogen content of manure can by lost through volatilization during storage in the earthen storage systems in the Prairie Provinces. The purpose of biological covers (biocovers), permeable, and impermeable covers is to reduce emissions of ammonia and other odorous gases. They do this in two ways: (1) physically limiting the emissions of ammonia and other gases from the surface of storage lagoons, and (2) creating a biologically active zone on the top of the covers where the emitted ammonia and other gases will be aerobically decomposed by microorganisms. The effectiveness of different covers in the reduction of ammonia emissions varies largely, and so do the costs. In the Netherlands the *Environmental Management Act* requires that that all manure storage facilities built after 1987 have to be covered. The act states that this measure should achieve a reduction of 75% of ammonia emissions. For a comparison of ammonia emissions from covered and uncovered manure storage facilities see Table 7.

A.7.1.2 Biocovers

Biocovers on outdoor manure storages have recently gained popularity in the United States and parts of Canada because they work very well, are easily managed and are affordable (Lorimer 2001). Permeable covers and biocovers include chopped barley, wheat, oats, or brome straw (8-12 inches thick). Their cost is estimated at $0.01 to $0.02 US per square foot. Chopped corn stalks (8 inches thick) cost less than $0.01 US per square foot, but are not as effective for ammonia control as straw. Biocovers cost about $0.10 per square foot per manure storage surface each time the cover is applied. Based on a 10- to 12-foot deep manure storage pit for finishing swine, the cost ranges from $ 0.50 to $ 0.80 US per head capacity or $0.25 to $0.40 US per pig marketed annually. A study conducted in Canada reported that the cost of barley straw covers was $41 per 1,000 square feet per year. Most biocovers last about two to three months and must be replaced each time manure is removed. Zahn et al. (2001) reported that ammonia emissions from lagoons could be reduced by 17-54% using a biocover. Xue and Chen (1999) reported that two layers (5 cm and 10cm) of wheat straw applied over an anaerobic liquid dairy manure lagoon were effective in reducing emissions rates of ammonia by 60-95%. Bicudo et al. (1999) evaluated the efficiency of combining different sizes of straw and geotextile covers in reducing ammonia emissions from manure storage. The findings of the study are illustrated in Figure 1. Geotextile cost is approximately $0.25 US per square foot, including application. Emissions Solution and Baumgartner Incs. (2000) tested the BioCap biocover in Colorado. Results of the test showed that the

Table 7. Ammonia reduction by using different covers.

Types of covers	Storage	NH_3 reduction (%)
Ridge covers	Lagoon/Storage tanks	> 80
Inflatable covers	Lagoon/Storage tanks	Up to 95
Floating covers (synthetic)	Lagoon/Storage tanks	45 to 95
Floating covers (natural)	Lagoon/Storage tanks	45 to 90

Table 8. Relative comparisons of ammonia emissions using different covers (Sommer et al. 1993).

Types of covers	Livestock	Ammonia emissions (g/m^2 day)
Uncovered, no crust	Pig	4.3
Uncovered, with crust	Pig	0.5-1.5
Uncovered, with straw	Pig	0.2-1.0
Covered, with lid	Pig	0.0-0.3
Uncovered, no crust	Beef	4.5
Uncovered, with crust	Beef	1.3
Covered, with lid	Beef	0.2-0.4

biocover achieved a 61-74% reduction in emissions of ammonia. In 2000, the State of Colorado approved BioCap™ as an alternative cover for manure storages in Colorado.

Permeable and impermeable covers

Research at Iowa State University found that a 95% reduction of NH_3 could be obtained by covering swine manure with 1.5 inches of Leca® (floating clay balls). Ammonia was reduced by 45-98% when impermeable and permeable floating plastic covers were used to cover swine manure storage tanks (Karlsson 1996; De Bode 1991). The cost of floating impermeable and permeable covers is estimated at about $0.35 to $0.45 US per pig marketed. Zhang and Gaakeer (1996) reported a reduction of 95% in ammonia emissions when an inflated cover with an operating pressure of 0.4 in. of H_2O was used. William and Nigro (1997) found that a supported, corrugated, plastic-coated steel cover reduced ammonia emissions by 68%. Miner and Suh (1997) showed that different polystyrene foam materials could reduce ammonia emissions up to 90%, compared to uncovered manure. Scotford and William (2001) conducted research to assess the practicalities and the cost of covering a swine liquid manure lagoon with 0.5 mm thick, reinforced, ultraviolet (UV) stabilized, black opaque polyethylene. They found that the floating plastic cover prevented 100% of ammonia emissions from the lagoon.

Manure management in barns

Frequent removal of manure from livestock buildings or pens is a good way to reduce ammonia emissions (Gustafsson 1997). Removing manure frequently to reduce ammonia is more effective with poultry than with swine as ammonia formation mainly takes place from the swine's urine (Heber et al. 2001). In poultry, the main source of inorganic N is uric acid (>70% of total N content), which is transformed into urea (Koerkamp 1994). Voorburg and Kroodsma (1992) reported that flushing the manure from the floor with water could eliminate NH_3 emissions from animal housing. Kroodsma et al. (1993) reported that flushing

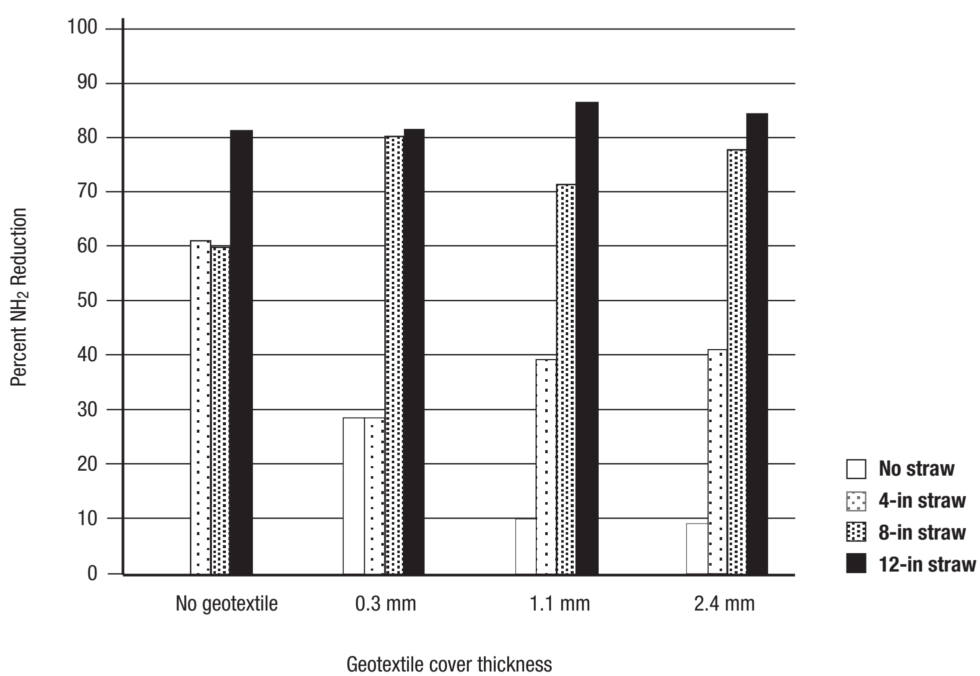

Figure 1. Percentage of ammonia reduction using geotextile covers Source: Bicudo et al. 1999.

floors with water reduced NH_3 emissions by 14-70%, compared to slatted floors in dairy housing. Ogink and Kroodsma (1995) concluded that an effective flushing method for slatted floors depends on the addition of compounds that supplement the effects of flushing. Voorburg and Kroodsma (1992) and Hoeksma et al. (1993), as cited by Arogo et al. (2001), reported that flushing frequency, and the quality and amount of water determine the amount of reduction that can be achieved. Lim et al. (2002) found that flushing and static pit recharge with secondary lagoon effluent had major effects on NH_3 rates. Flushing has the disadvantage of increasing manure volume, thereby increasing transportation and application costs.

A.7.2 Inhibition Methods

A.7.2.1 Manure additives

Arogo et al. (2001) reported that the criteria for NH_3 reducing manure additives are:

1. If they directly adsorb NH4+ and NH3.
2. If they reduce the manure pH.
3. If they promote microbial production of organic acids that reduce the manure pH.
4. If they increase microbial N immobilization.
5. If they inhibit microbial growth.

McCrory and Hobbs (2001) have done a comprehensive review of the digestive, acidifying, adsorbent and urease inhibitor additives that can be added to manure to slow down or inhibit the release of ammonia from livestock manure. Varel (1999) and Varel et al. (1999) reported that adding urease inhibitors to livestock manure has shown promising results for reducing ammonia emissions from livestock buildings. Heber et al. (2000) tested and evaluated a new manure additive called Alliance™, developed by Monsanto EnviroChem (St. Louis, MO). According to the data collected in this experiment, producers can expect up to a 70% reduction in ammonia gas generation and concentration in their deep-pit finishing buildings with the use of Alliance™. They attributed the reduction of NH_3 emissions from the manure pits to dilution of manure content by Alliance™. Stevens et al. (1989) showed that addition of sulfuric acid to cattle and swine manure reduced ammonia emissions. Subair et al. (1999) found that the addition of paper products to liquid swine manure reduced ammonia by 29-47% by increasing the carbon/nitrogen ratio of the liquid hog manure.

Moore et al. (1995) reported that alum addition to poultry manure resulted in a 99% decrease in ammonia emissions. Alum additions have also been shown to decrease ammonia from beef cattle manure (Cole and Parker, 1999). Meisinger et al. (2001) reported that addition of 2.5% alum to raw dairy slurry reduced ammonia volatilization by 60%. The poultry industry in the United States extensively uses Poultry Litter Treatment (PLT), a dry granular additive to control ammonia in poultry houses.

The ability of some manure amendments to suppress the emissions from simulated beef cattle feedlot surfaces has been investigated by Shi et al. (2001). These amendments include alum [$Al_2 (SO_4)_3$], calcium chloride ($CaCl_2$), brown humate, black humate, and urease inhibitor N- (n-butyl) thiophosphoric triamide (NBPT). Their study proved that ammonia emissions from simulated open-lot feedlot surfaces could be reduced by 26.4-98.3% using a variety of manure additives. Parker et al. (2001) demonstrated in a laboratory study that using additives can substantially reduce ammonia emissions from simulated feedlot surfaces. They reported that the cost of the amendments, if they are applied only once at the beginning of the feeding period, ranged from $0.12 to $5.35 US per head.

The use of manure additives may not be economically feasible. The costs of the other chemical additives vary widely, and they can be cost prohibitive for smaller operations. One disadvantage of using acidifying agents to suppress the ammonia emissions from manure is that it will favour the condition for the release of more hydrogen sulfide to the environment.

A.7.2.2 Diet manipulation

Ammonia and other nitrogenous gases result from the digestion of protein, part of which is lost in manure and urine. Growing pigs, for example, excrete 70% of the protein in feed while beef cattle excrete 80–90% and broiler chickens 55% (Jongbloed and Lenis, 1992). Diet manipulation could be a solution for reducing ammonia emissions from swine manure (van Kempen and van Heugten, 1998). A study conducted by Phillips et al. (1999) assessed ways of abating emissions from livestock buildings and manure storage facilities in the U.K. A literature review was conducted, and all available ammonia abatement techniques were ranked according to criteria such as efficacy, achievable abatement, and capital and running cost of these techniques. The results of the ranking techniques indicated that diet manipulation is the best approach over a wide range of applications.

Carefully matching feed to the nutritional requirements of pigs could reduce N excretion without affecting productivity (Jongbloed and Lenis 1992; Hobbs et al. 1996). Kay and Lee (1997) found an 11% decrease in manure volume for each 1% reduction of the pig's dietary crude protein. Turner et al. (1996) conducted a laboratory study to evaluate the emissions of NH_3 from manure pits as affected by the feeding of amino acid-supplemented and phytase-supplemented diets versus conventional diets to growing finishing pigs. They reported that the amino acid-supplemented diets significantly suppressed the levels of NH_3 measured above the simulated pits. Sutton et al. (1996) also tested the effect of amino acid-supplemented diets on NH_3 emissions. They obtained results that were in general agreement with those obtained by Turner et al. (1996). Godbout et al. (2001) evaluated the impact of three specific formulations (18% protein, 16% protein, and 16% protein plus fermented carbohydrates) on odour and gas emissions from grower-finisher swine buildings. They reported that diet formulation significantly reduced NH_3 rates. Canh et al. (1997) found that on average ammonia emissions decreased about 15% for each 5% increase of a pressed sugar beet silage (PSBS) in pig diets. Van Kempen (2000) showed that adipic acid supplementation to pig diets reduced ammonia emissions by 25%, which corresponded to the predicted reduction in ammonia emissions based on the reduction in manure pH observed. Sutton et al. (2001) documented the findings of numerous studies that investigated the effect of the diet manipulation on controlling gaseous and odorous compounds from livestock buildings. They concluded that the manipulation of the pig's diet is a feasible and practical method to minimize the production and emission of gaseous compounds such as NH_3 and H_2S.

A study was conducted by McGinn et al. (2002) in Lethbridge, Alberta to investigate the effect of three barley-based diets on manure composition and on the ammonia and volatile fatty acids (VFA) from beef feedlot manure. The results of this study suggest that the metabolizable protein requirements of heavyweight feedlot cattle (400 to 550 kg) were met when finished on a barley grain and barley silage diet [12.9% crude protein (CP)]. Therefore, the ability to reduce total N content of manure or manipulate the route of N excretion is limited, unless lower protein ingredients, such as corn silage or cereal straw, were incorporated into the diet to lower the basal diet CP concentration. Paul et al. (1998) and Frank (1999) reported that a decrease in dietary CP concentration to dairy cows is the most common method to reduce nitrogen excretion in manure. James et al. (1999) found that increased dietary crude protein concentration increased N intake, N excretion, urea-N excretion, and N excreted in urine by the heifers. They also found that dietary manipulation of N intake by a reduction of 14.0% (dry matter basis) resulted in a 28.1% decrease in ammonia emissions and decreases in the urea N, total N, and percentage N excreted in urine of 29.6%, 19.8%, and 7.4%, respectively.

Gates et al. (2000) conducted a research study to test the hypothesis that reducing dietary crude protein below commercial levels, with simultaneous enhancement of amino acid (AA) levels will result in NH_3 reduction from poultry litter. They found that NH_3 emissions decreased significantly with the decreased levels of CP in the diet. Other studies have found that a 1% reduction in dietary crude protein decreases nitrogen excretion by 10% in poultry (Van der Peet-Scwering 1997; Aarnink et al. 1993; Van Cauwenberghe and Burnham 2001).

A report by C2C Zeolites corporation indicated that zeolites fed to pigs at rates up to 5% of feed in a study by McGill University showed improved net food conversion as well as improved air quality and reduced ammonia levels. Calculated net benefits of adding zeolites to rations are between $7.75 and $10.20 CAN per finished hog.

The introduction of multi-phase feeding strategies has been very successful in helping to balance AA and digestible protein in livestock diets. Lenis (1989) and Coppoolse et al. (1990) found a decrease of 6% in N excretion through the introduction of multi-phase feeding in pigs. Van der Peetchwering (1997) showed that when different housing and manure management systems were combined with a multi-phase feeding regime (high nitrogen feed mixed with low nitrogen in different ratio per week), ammonia emissions were reduced by 45%. Using split-sex feeding is also found to be very effective in enhancing nutrient efficiency and reduce nutrient excretions. Groenestein et al. (2003) studied the effect of feeding schedule on ammonia emissions from housing systems for sows. They concluded that changing the feeding schedule alters the diurnal patterns of the ammonia emission, but if the animals are fed simultaneously, changing the feeding time does not affect the total amount of ammonia emitted. However, with animals fed sequentially, the ammonia emission was reduced by 10% if the feeding starts in the afternoon instead of morning.

No cost information for diet manipulation is available in the literature review, but some studies suggested that diet manipulation has the potential to reduce the cost of feed. Additional research is needed to find if diet manipulation has any adverse effects on livestock health, products quality or productivity.

A.7.2.3 Floor modification

The type and amount of floor area exposed to manure in animal housing facilities can have a significant impact on the emissions rate of NH_3. Hoeksma et al. (1993) and Aarnick et al. (1997) reported that NH_3 emissions from fattening swine buildings were reduced from a 3.5 to a 2.0 kg emissions rate of NH_3/pig space per year by lowering the slatted floor area percentage from 100 to 25%. Ni et al. (1997) studied the status of floors in swine finishing buildings and their effect on the emissions of ammonia. They concluded that a floor factor is positively correlated with the ammonia emissions rate. They also found that at high floor factor, the ventilation rate and the inside temperature have a measurable impact on the NH_3 emissions rate.

In another study a 46% reduction of NH_3 was obtained when a grooved concrete floor with perforation and scraper was compared to the slotted floors of free-stall cow housing (Swierstra et al. 1995; Braam et al. 1997a; Swierstra et al. 2001). Aarnik (1997) conducted an experiment to test the effect of different types and configurations of floors on the emissions of ammonia in swine housing. They found that NH_3 from a metal slatted floor was reduced by 27% when compared to concrete slatted floors (10 cm wide with 2 cm gaps). Groenestein et al. (1992) measured a reduction in ammonia of 23 to 57% in a deep litter pig facility in comparison to fully slatted floor units.

A.7.3 Capture and Control Methods

A.7.3.1 Biofiltration

Biofiltration is an effective method for reducing the emissions of NH_3, odour and H_2S from livestock buildings (Nicolai and Janni, 1997, 1998). Biofilters usually consist of ventilation fans that exhaust air from the building through ducts into a plenum below the biofilter media. The air passes through the biofilter media where the microorganisms treat it before it is emitted into the atmosphere (Figure 2).

The performance of biofilters is usually affected by ambient conditions such as temperature and ammonia concentration in the air stream. It is also affected by other factors such as the oxygen level, acidity and moisture content of the biofilter medium. Moisture content of the medium is critical to the performance of any type of biofilter. Lorimer et al. (2001) reported that European style biofilters have been tested and evaluated in some swine facilities in Minnesota. They achieved NH_3 reductions of 50-60%. Sheridan et al. (2000) evaluated the NH_3 removal efficiency of two biofilters. The first one used wood chips larger than 20 mm as media and the second one used wood chips between 10 and 16 mm. Ammonia reductions of 89% and 95% were attained by biofilter system 1 and 2, respectively. Martens et al. (2001)

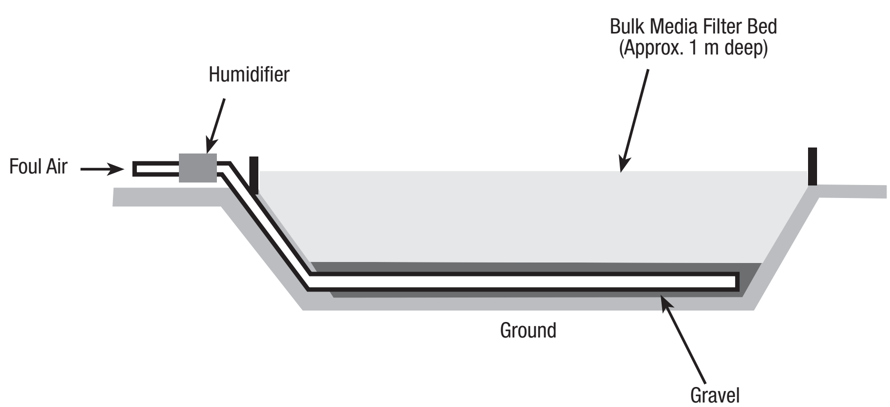

Figure 2. Open soil biofilter Source: Burgess et al. 2001.

tested five identical biofilters units, each filled with different filter materials and connected to a pig facility. They reported that in comparison to odour reduction those biofilters were not suitable for ammonia reduction. Martinec et al. (2001) reported ammonia emissions reduction of about 9-33% by using a biofilter with a filter volume load of 450-500 m^3/m^3h. Hartung et al. (2001) evaluated the performances of a mature (6.5 year old media) and new biofilter (new media). The media consisted mainly of coconut fiber and peat fiber mixture. They reported a reduction on ammonia emissions of 15-36% when an ammonia load of 4475 $mg/m^3/h$ passed through the biofilter. They also reported that the biofilter's efficiency decreases as the airflow rates increase. Siemers and Vanden Weghe (1997) showed that a combination of a biofilter-wet scrubber system achieved a 17-38% reduction of ammonia from swine facilities. They suggested that this approach is not economically feasible since it costs $3-10 US per pig per year. Limited economic information suggests that biofiltration is cost effective. Depending on the design, the total construction and operating cost for 3 full size biofilters installed on 700-sow gestation/farrowing swine building over three years were $0.22 US per piglet (Nicolai and Janni 1998). Boyette (1998) estimated that operating and maintaining a biofilter would cost $2-14 US per cubic foot per minute (cfm) of capacity for exhausted gas treated.

A.7.3.2 Oil sprinkling

Oil sprinkling is an emerging technology that is a promising control measure for air pollutants inside livestock buildings. A 30% reduction of NH_3 by using vegetable oil was reported by Zhang et al. (1996). Dorota et al. (2001) showed that daily sprinkling of soybean oil inside swine finishing buildings using a soaker system significantly reduced the indoor concentration and emissions of NH_3. Pahl et al. (2000) conducted a study to investigate and assess the effect of foam and oil cover on the emissions of ammonia from manure surfaces stored in pits in swine buildings (Table 9). Pahl et al. (2000) estimated manure treatment with oil can incur an annual cost of $ 4.68 US per pig place. They found that applying vegetable oils to swine manure could achieve a considerable reduction in ammonia emissions (50%). Derikx and Aarnik (1993) found that mineral oil has proven to be effective in the reduction of up to 90% of ammonia emissions compared to untreated manure. Buscher et al. (1997) obtained ammonia reductions of 46%, 53% and 64%, respectively, by addition of 20, 40 and 60 liters of canola oil mix per cubic meter of manure.

Pahl et al. (2000) cited Davies and Rudd (1998) who reported that oil-treated manure could present a problem for land spreading of manure because the oil can have adverse effects on the soil and sub-surface watercourse but manure with less than 4% oil content is considered safe for land application in U.K.

A.7.3.3 Temperature control

Many environmental factors determine ammonia emissions rates from livestock facilities such as wind speed and temperature. By controlling these factors, ammonia emissions could be under control. Arogo et al. (1996) reported that the decay rate of ammonical concentration increased with an increase in manure temperature. Zhang et al. (1994) showed that lower temperature in slurry storages reduced the conversion rate of organic to ammoniac nitrogen and may reduce the diffusion rate of NH_3 in slurry storage. Anderson (1995) found a significant correlation between manure temperature and ammonia emissions. Steenvoorden et al. (1999) found a positive relationship between ammonia and ambient inside temperature of a mechanically ventilated dairy barn (Table 10). Rom et al. (2000) reported a reduction of 40-50% in ammonia emissions due to the reduction of the room and manure temperature. Anderson et al. (1996) found that by reducing manure temperature

Table 9. Reduction in ammonia emissions (%) after application of oil Source: Pahal et al. 2000.

Treatment	Depth of oil		
	3 mm	6 mm	12 mm
After oil added	63%	94%	95%
After rain	90%	98%	98%
After mixing	91%	99%	98%

Table 10. Correlation between ammonia emissions and temperature inside dairy barn *Source: Steenvoorden et al. 1999.*

Month	Temperature (°C)	Temperature (°F)	Emissions (g N/animal/day)	Volatilization (%)
January	11.8	53	25.6	7.4
February	12.4	54	28.4	8.1
March	14.4	58	29.1	8.3
April	14.1	57	30.1	8.3
May	18.4	65	39.9	11.3

from 15 to 10°C the emissions of ammonia were reduced by 40%.

Voermans et al. (1996) reported that an NH_3 emissions reduction of up to 50% could be achieved by lowering the temperature of the manure only. A manure surface-cooling channel has been developed in the Netherlands. The system consists of a number of floating fins filled with water, installed in swine manure pits. The floating fins cool the surface of the manure. Compared to the fully slatted floor, the ammonia reduction is 75%. This measure has been shown to be effective but expensive (Anderson 1995). Cooling the top 4 inches of slurry to 15°C or lower by recirulating groundwater in a ground loop geothermal system has reduced ammonia emissions in hog nurseries. The initial cost was $ 45.00 CAN per pig space and annual cost was $6.58 CAN per pig space. Den Brok and Verdoes (1997) tested a manure pit cooling system in a manure pit in a swine building. They found that ammonia emissions could be reduced by 44%. The annual cost of this system is about $16.50 CAN per pig space. Moal et al. (1995) reported that air and soil temperature are important factors that affect ammonia emissions during manure application. Higher soil temperature will result in higher ammonia emissions rates.

A.7.3.4 Bioscrubbing

The concept of bioscrubbing is similar to biofiltration. Both rely on microbial degradation of NH_3. The difference between bioscrubbing and biofiltration is that the bioscrubber is housed in a closed tower containing water. When ammonia passes through the tower, it will be captured and absorbed by water, then oxidized by the microorganisms (Figure 3). Lais (1997) reported that bioscrubbing could achieve an 89% reduction in ammonia emissions. Lorimer (2001) reported that a bioscrubber used in swine finishers reduced NH_3 by 33-50%. Feddes et al. (2001) found that bioscrubbers removed 80% of the NH_3 from the air exhausted from an enclosed dunging area (EDA) for growing pigs. No estimate of the cost of bioscrubbing to reduce ammonia emissions was found, but Nielsen and Pain (1991) reported that the use of bioscrubbers to purify air in livestock housing is generally limited by the high cost of the equipment.

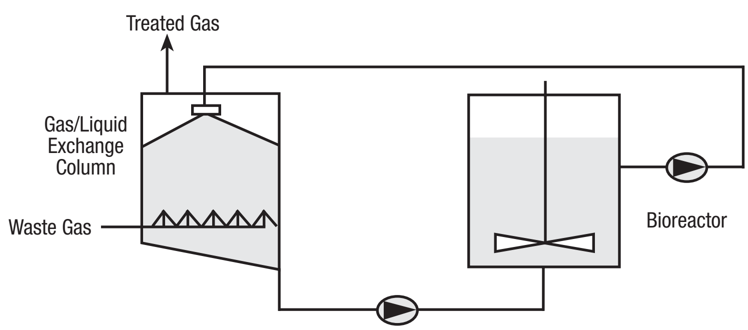

Figure 3. Bioscrubber *Source: Burgess et al. 2001.*

A.7.3.5 Ozonation

Ammonia reacts with ozone and gives stable products (nitrogen gas): $4NH_3 + 4O_3 \rightarrow 2 N_2 + 6H_2O + 3O_2$. Ozonation is rarely used to reduce ammonia emissions from livestock buildings; however, a study by Priem (1977) found that ammonia emissions could be reduced by 15 and 50% during summer and winter, respectively. Hill and Barth (1976) found that ozone was effective in eliminating ammonia and methylamine. A study by North Carolina State University found that treating the air in a swine finishing building with ozone reduced ammonia emissions by 58% (Bottcher et al. 2000). Keener et al. (1999) found that an ozonated swine-finishing house had significantly less ammonia and total dust than the control house. A study conducted by North Carolina State University (NCSU 1998) estimated that ozonation of indoor air of a swine building will cost approximately $6-11 US per unit of pig production capacity.

A.7.4 Manure Application Methods

Ammonia losses (Table 11) due to manure spreading on land are mainly due to the following factors: (1) temperature, wind velocity, humidity, and rainfall at the time of spreading; (2) the length of time between spreading and incorporating the manure into the soil; (3) type of manure; and (4) application technique (Brunke et al. 1988; Morken and Sakshaug 1998). The rate of ammonia emissions will be reduced if manure is spread in winter because ammonia losses are directly affected by wind speed and temperature, which are normally low in winter months (Mattila 1998; Sommer and Jacobsen 1999; Smith et al. 2000; Hoff et al. 1981; Pain et al. 1989; Thompson et al. 1990; Sommer et al. 1991). However, manure application on frozen soils is not recommended because of the possibility of runoff contamination in spring. Burton (1997) reported that NH_3 emissions could be managed by applying manure to land in such a way that reduces contact-area between liquid manure and the atmosphere. Pain and Misselbrook (1991) found that ammonia emissions could be reduced by 20% when urine and solid manure were applied separately.

A.7.4.1 Injection

Injection or rapid incorporation of the manure into the soil are the most effective ways to reduce ammonia emissions following application. With these techniques, the release of ammonia can be reduced by more than 90% (Malgeryd 1996). Injection or immediate incorporation of manure into the soil reduces NH_3 losses compared to other surface application methods (Hoff et al., 1981; Thompson et al. 1987; Phillips et al. 1991; Sommer and Thomsen 1993; Smith et al. 2000, Malgeryd, 1996). Kowalewsky (1990) found that losses were reduced by 75 % if injected 2 to 3 cm.

Table 11. Effect of different manure application methods on NH_3 reduction. Source: Hendriks and van de Weendhof 1999.

Control measure	Type of manure	Land use	Emissions reduction (%)
Band-spreading	Liquid	Grassland	10
Band-spreading	Liquid	Arable	30
Trailing shoe	Liquid	Mainly grassland	40
Injection (open slot)	Liquid	Grassland	60
Injection (closed slot)	Liquid	Mainly grassland, arable land	80
Incorporation	Solid manure and liquids	Arable land	80

Surface placement methods such as band spreading using trailing hoses, shoes, and shallow slot injection (up to 50 mm depth) reduced NH_3 loss by 40-60 % of the total ammoniacal nitrogen (TAN) applied compared with surface broadcasting (Smith et al. 2000). Research in the U.K. has shown that shallow injectors and band spreaders can decrease ammonia emissions under U.K. conditions by 50-80% compared with more conventional broadcasting (Pain and Jarvis, 1999). Incorporation of manure immediately after spreading by different mean of cultivation could result in reducing ammonia losses substantially (Van Dongen 1991; Amberger 1991; van der Molen et al. 1990). Meisinger and Jokela (2002), in a series of wind-tunnel studies in Beltsville Maryland, found losses from unincorporated manure amount to 45% of the applied NH_4-N, while losses after immediate tillage with a chisel plow, tandom-disc harrow, or moldboard plow were 9%, 5%, and 1%, respectively. A Sub Soil Deposition (SSD) applicator that bands the manure over vertical slots made by a soil aerator (Aerway, Wylie TX, Norwich ON, and Surrey, B.C.) has been developed by Pacific Agri-Food Research Centre (PARC) in Agassiz, B.C. (Bittman, 1999). The SSD reduced ammonia from grassland by 45-50%.

A.8 Research Gaps and Needs

From scanned literature, most emissions control strategies were solely directed toward finding emissions control measures in relation to technical characteristics. No relation was established to assess the actual environmental impact of the emissions. In addition, no studies have been carried out to see the readiness of the producers to adopt and embrace the emissions control technologies.

Based on the areas of strength and gaps in knowledge determined through this literature review, the areas of research are suggested to provide a better understanding of the NH_3 and H_2S atmospheric emissions due to manure production and application are described in section C.

A.9 References

Aarnink, A.J.A., P. Hoeksma and E.N.J. Van Ouwerkerk. 1993. Factors affecting ammonia concentration in slurry from fatting pigs. In Nitrogen flow in pig production and environmental consequences. Verstegen, M.W.A., L.A. Den Hartig, G.J.M. Van Kempen, and J.H.M. Metze edit). 413-420, Pudoc Scientific Publisher. Wageningen.

Aarnink, A.J.A. and A. Elzing. 1998. Dynamic model for ammonia volatilization in housing with partially slatted floors for fattening pigs. Livestock Production Science 53:153-159.

Aarnink, A.J.A., D. Swiestra, A.J. van der Berg and L. Speelman. 1997. Effect of type of slatted floor and degree of fouling of solid floor on ammonia emission rates from fattening piggeries. Journal of Agricultural Engineering Research 66:93-102.

AAFC, Agriculture and Agri-Food Canada. 1998. Research strategy for hog manure management in Canada. Multidisciplinary task force final report on the effect of hog production on the environment.

Agriculture, Nature Management and Fisheries (ANMF). The Netherlands. 1995. Policy document on manure and ammonia.

Allen A.G., R.M. Harrison and M.T. Wake. 1988. A meso-scale study of the behavior of atmospheric ammonia and ammonium. Atmospheric Environment 22:1347-1353.

Amberger, A. 1991. Ammonia during and after land spreading of slurry. In: Odour and ammonia from livestock farming, eds. V.C. Nielsen, J.H. Voorburg and P. L'Hermite, 126-131. New York: Elsevier Applied Science.

Amon, M., M. Dobeic, R. W. Sneath, V.R. Phillips, T. H. Misselbrook and B.F. Pain. 1997. A farm-scale study on the use of clinoptilolite zeolite and de-odourase ® for reducing odour and ammonia from broiler houses. Bioresource Technology 61:229-237.

Anderson, M. 1995. Cooling of manure in manure culverts. Swedish Agricultural University, Institute of Agricultural and Biosystems Technology. Specialmeddlelande 218.

Anderson, M. 1995. Ammonia volatilization from cow and pig manure: results from laboratory studies with a new climate pig chamber. Swedish University of Agricultural Sciences. Department of agricultural biosystems and technology. Report 98. Alnarp.

Anderson. M. 1996. Performance of bedding materials in affecting ammonia from pig manure. Journal of Agricultural Engineering Research. Vol. 65, No. 3, November 1, 1996.

Aneja, V. P., J. P. Chauhan, and J. T. Walker. 2000. Characterization of atmospheric ammonia from swine waste storage and treatment lagoons. Journal of Geophysical Research 105:11535-11545.

Aneja, V. P., B. Bunton J. T. Walker, and B. P. Malik. 2001. Measurement and analysis of atmospheric ammonia from anaerobic lagoons. Atmospheric Environment 35:1949-1958.

ApSimon, H. M., M. Kruse and J. N. B. Bell. 1987. Ammonia and their role in acid deposition. Atmospheric Environment 21:1939-1946.

ApSimon, H.M. and M. Kruse-Plass. 1991. The role of ammonia as a atmospheric pollutant. In Odour and Ammonia Emissions from Livestock Farming , eds. V.C. Nielsen, J.H. Voorburg and P. L'Hermite, 17-20. New York:Elsevier Applied Science.

Arogo, J., P. W. Westerman, A. J. Heber, W. P. Robarge and J. J. Classen. 2001. Ammonia emissions –A review. ASAE paper No. 014089.

Arogo, J., and P. W. Westerman. 2002. Proposed method for determining ammonia emissions factors from confined swine feeding operations. ASAE paper No. 024085.

Asman, W. A. H. 1992. Ammonia emissions in Europe: Update emissions and emissions variation. Report prepared by national Institute of Public Health and Environmental Protection, Bilthoven.

Asman, W. A. H. 1998. Factors influencing local dry deposition of gases with special references to ammonia. Atmospheric Environment 32:415-421.

ATSDR (Agency for Toxic Substances and Disease Registry). 1990. Toxicological profile of ammonia. NITS order number PB/91/180315/AS.CDC. Atlanta, Ga. USA.

Battye R., W. Battye, C. Overcash, and S. Fudge. 1994. Developments and selection of ammonia emissions factors: Final Report. EC/R Inc., Durham, NC. EPA Contract Report #68-D3-0034, U. S. Environmental Protection Agency, Research Triangle Park, NC. 111 pp.

Beauchamp, E. G., G. E. Kidd, G. Thurtell. 1978. Ammonia volatilization from sewage sludge applied in the field. J. of Environmental Quality, Vol. 7 (1), pp. 141-146.

Berckmans, D., J. Q. Ni, J. Roggen, G. Huyberechts. 1992. Testing an ammonia sensor for livestock buildings. ASAE paper No. 92-4522.

Bicudo, J.R. , J.J. Classen, C.D. Goldsmith Jr. and R. Smith 1999. Reduction of nutrient and odor in swine manure with sequencing batch treatment and intermitted aeration. ASAE paper No 99-4049

Bicudo, J. R., and C. J. Clanton. 2001. Odour control technology evaluation: Geotextile fabric cover. Final report to National Pork Board. Des Moines, Iowa.

Bittman, S.C.G. Kowalenko, D.E. Hunt and O. Schmidt. 1999. Surface-banded and broadcast dairy manure effect on tall fescue yield and nitrogen uptake. Journal of Agronomy 91(5) 826-833.

Bottcher, R.W., K.M. Keener and R.D. Munilla. 2000. Comparison of odor control mechanisms for wet pad scrubbing, indoor ozonation, windbreak walls, and biofilters. ASAE Paper 00-4091, ASAE, St. Joseph, MI 49085.

Braam, C. R., J. J. M. H. Ketelaar, and M. C. J. Smits. 1997a. Effects of floor design and floor cleaning on ammonia emissions from cubicle houses for dairy cows. Netherlands J. Agricultural Sciences. 45:49-64.

Braam, C. R., M. C. J. Smits, H. Gunnink and D. Swiestra. 1997b. Ammonia emissions from a double-sloped solid floor in a cubicle house for dairy cows. Journal of Agricultural Engineering Research 68:375-386.

Brook, J. R., L. Zhang, F. Di-Giovanni and J. Padro. 1999. Description and evaluation of a model of deposition velocities for routine estimates of air pollutant dry deposition over North America; Part I: model development. Atmospheric Environment 33(30): 5037-5051.

Brunke, R., Alvo, P., Schuepp, P. and Gordon, R. 1988. Effect of meteorological parameters on ammonia loss from manure in the field. J. Environ. Qual. 17:431-436.

Bundy, D. S., and S. J. Hoff. 1998. The testing procedure and the results of pit additives tested at Iowa State University. In animal production systems and the environment. An International Conference on Odour, Water Quality, Nutrient Management and Socioeconomic Issues, Vol1: 279-285, Des Monies, Iowa, Iowa State University.

Bussink, D.W. and O. Oenema. 1998. Ammonia volatilization from dairy farming systems in temperate areas: a review. Nutrient Cycling in Agroecosystems 51:19-33.

Burgess, J. E., Parsons, S.A. and Stuetz, R. M. 2001. Developments in odour control and waste gas treatment biotechnology: A review, Biotechnology. Adv., 19, 35-63.

Burton, C.H. 1997. Manure management-treatment strategies for sustainable agriculture. Silsoe Research Institute, Bedford, UK. 181 pp.

Buscher, W., E. Hartung 2, T. Jungbluth 2. 1997. Examining the performance of additives in reducing the odour and ammonia from slurry with a standard test procedure. ASAE Paper No 97-4121.

Canh, T.T., A.J.A. Aarnink, J.W. Schrama and J. Haksma.1997. Ammonia emissions from pig houses affected by pressed sugar beet pulp silage in the diet of growing–finishing pigs. Proceeding of international symposium on ammonia and odour control from animal production facilities. Vinkeloord, The Netherlands. Oct 6-10, 1997.

Carr, L.E., F.W. Wheaton and L.W. Douglass. 1990. Empirical models to determine ammonia concentration from broiler chicken litter. Transaction of ASAE. 33(4): 1337-1342.

Charles, D. R and C. G. Payne. 1966. The influence of graded levels of atmospheric ammonia on chicks. I. Effects on the performance of laying hens. Brit Poultry Science. 7:177-187.

Chetner, S. and D. Sasaki.2001. Agricultural air emissions inventory for Alberta. Literature review prepared for intensive livestock operations working group.

Clanton, C. J., D. R. Schmidt, R. E. Nicolai, L. D. Jacobson. P. R. Goodrich, K. A. Janni and J. R. Bicudo. 2001. Geotextile fabric-straw manure storage cover for odour, hydrogen sulfide, and ammonia control. Applied Engineering in Agriculture. 17(6): 849-858.

Cole, N. A. and D. B. Parker. 1999. USDA-Agricultural Research Service, Bushland, Texas and West Texas A&M University, Canyon, Texas.

Coppoolse, J.A.M. Van Vuuren, J. Huisman. W. M.M. A. Janssen, A.W. Jongbloed, N.D. Lenis and P.C. and M. Simons.1990. The excretions nitrogen, phosphorus and Potassium by farm animal, now and tomorrow. Dienst Landbouwkundig ondeerzoek, Wageningen. The Netherlands.

Crook, B. J. E. Robertson, S. A. TraversGlass, E. M. Boothroyd, J. Lacey and M. D. Topping. 1991. Airborne health hazards in the piggery. American Industrial Hygiene Association Journal. 52(7): 271-279.

De Bode, M. J. C. 1991. Odour and ammonia emissions from manure storage. In ammonia and odour emissions from livestock production, eds. V.C. Nielsen, J. H. J. H. Voorburg, and P. L'Hermite, 59-66. London: Elservier Applied Sciences Publisher.

Demmers, T. G. M., L. R. Burgess, J. L. Short, V. R. Phillips, J. A. Clark and C. M. Wathes. 1998. First experiences with methods to measure ammonia from naturally ventilated cattle buildings in the U.K. Atmospheric Environment 32:283-293.

Demmers, T. G .M., L. R. Burgess, J. L. Short, V.R. Phillips, J. A. Clark and C. M. Wathes. 1999. Ammonia from two mechanically ventilated UK livestock buildings. Atmospheric Environment 33:217-227.

Den Brok, G. M. and N. Verdoes. 1997. Slurry cooling to reduce ammonia emissions from pig houses. Proceeding of international symposium on ammonia and odour control from animal production facilities. Vinkeloord, The Netherlands. Oct 6-10, 1997.

Denmead, O. T., J. R. Freney and J. R. Simpson. 1982. Dynamic of ammonia volatilization during furrow irrigation of maize. Soil Sci. Soc. J. 46: 149-155.

Derikx, P. J. L. and A. J. A. Aarnik. 1993. Reduction of ammonia emissions from slurry by application of liquid top layers. In Nitrogen flow in pig production and environmental consequences. Edited by M.W.A. Verstegen, L.A.den Hartog, G.J.M. van Kempen and J.H.M. Metz, pp 344-349.

Dorota, A. P., L. D. Jacobson V. J., Johnson and R. E. Nicolai.2001. Design and Management of an Oil Sprinkling System to Control Dust, Odor, and Gases in and from a Curtain-Sided Pig Finishing Barn. ASAE paper No: 014076

Emerson, K., R. C. Russo, R. E. Lund, and R.V. Thurston. 1975. Aqueous ammonia equilibrium calculations: Effect of pH and temperature. J. of the Fisheries Research Board of Canada, Vol. 32, pp. 2379-2383.

Feddes, J., I. Edeogu, B. Bloemendaal, S. Lemay and R. Coleman. 2001. Odour reduction in a swine barn by isolating the dunging area pp. 278-284 in Livestock Environment VI: Proceedings of the 6th International Symposium (21-23 May, Louisville, Kentucky, USA) ed. Richard R. Stowell, Ray Bucklin, and Robert W. Bottcher. Pub. Date 21 May 2001. ASAE Pub #701P0201.

Ferm, M. 1998. Atmospheric ammonia and ammonium transport in Europe and critical loads: a review. Nutrient cycling in agroecosystems. 51:5-17.

Flint, T. A., K.C. Persaud and R. W. Sneath.2000. Automated indirect method of ammonia flux measurement for agriculture: effect of incident wind angle on airflow measurements. Sensors and Actuators B 69: 389-396.

Freney, J. R., J. R. Simpson, and O. T. Denmead. 1983. Volatilization of ammonia. In: Freney, J.R. and Simpson, J.R. (Hrsg.), Gaseous loss of nitrogen from plant-soil systems. Martinus Nijhoff, pp. 1-33. The Hague.

Gates, R. S., J. L. Taraba, K. Liberty, A. J. Pescatore, A. H. Cantor, M. J. Ford, and D. J. Durnham. 2000. Dietary manipulation for reduced ammonia and TAN in broiler litter. In Conference proceeding: second international conference on air pollution from agricultural operations. Des Moines, Iowa. pp.147-156.

Godbout, S., S. P. Lemay, R. Joncas, J. P. Larouche, D. Y. Martin, J. F. Bernier, R. T. Zijlstra, L. Chénard, A. Marquis, E. M. Barber, and D. Masse´. 2001. Oil sprinkling and dietary manipulation to reduce odour and gas from swine buildings-Laboratory scale experiment. pp. 671-678 in livestock environment VI: Proceedings of the 6th international symposium. 21-23 May 2001. Louisville, Kentucky, USA.

Goodrich, P. R. Y., H. Ma. Wang, S. Deng, and R. R. Ruan. 1999. Odour destruction using a barrier discharge reactor. ASAE paper No. 99-4034.

Goss, M. J, J. R. Ogilvie, E. G. Beauchamp, D. P. Stonehouse, M. H. Miller and K. Parris. 1994. Current state of the art on manure/nutrient management. COESA Report: RES/MAN-001/94

Groenestein, C. M., J. Oosthoek, H. Montsma and B. Reitsma. 1992. The emissions of ammonia and other nitrogen compounds from deep-litter systems for fattening pigs: a field study. In: Proceedings workshop deep-litter systems for pig farming, 1992. Eds. J.A. Voermans. Research Institute for Pig Husbandry, Rosmalen, Netherlands.

Groenestein, C. M, M. M. W.B. Hendriks and L.A. den Hartog. 2003. Effect of feeding schedule on Ammonia emission from individual and group housing systems for sows. Biosystems engineering. Volume 85, Issue 1, May 2003, pp79-85.

Groot Koerkamp, P. W. G., J. H. M. Metz, G. H. Uenk, V. R. Phillips, M. R. Holden, R. W. Sneath, J. L. Short, R. P. White, J. Hartung, and J. Seedorf. 1998. Concentrations of ammonia in livestock buildings in Northern Europe. J. Agric. Eng. Res. 70(1): 79-95.

Gustafsson, G. 1997. Investigations of factors affecting air pollutants in animal houses. Annuals of Agricultural Environmental Medicine, 4: 203-215.

Harper, L.A., R.R. Sharpe and T.B. Parkin. 2000. Gaseous nitrogen emissions from anaerobic swine lagoons:Ammonia, nitrous oxide and dinitrogen gas. Journal of Environmental Quality 29:1356-1365

Harris, D. B, E. L. Thompson, R. A. Hashmonay Jr., D. F. Natschke, and K. Wagoner, M. G. Yost. 2001. Field evaluation method of estimating gaseous flux from area sources using open path Fourier Transform Infrared Spectroscopy (FTIS). Environmental Sciences and Technology.

Hartung, J. and V. R. Phillips. 1994. Control of gaseous from livestock buildings and manure stores. Journal of Agricultural Engineering Research, 57:173-189.

Hartung, E., and W. Buscher. 2001. Reduction in ammonia and odour emissions from a piggery with biofilters. Transaction of ASAE, 44(1): 113-118.

Heber, A. J., J. Q. Ni, T. T. Lim, C. A. Diehl, A. L. Sutton, R. K. Duggirala, B. L. Haymore, D. T. Jelly and V. I. Adamchuk. 2000. Effect of a manure additive on ammonia emissions from finishing buildings. Transactions of the ASAE, 43:1895-1902.

Heber, A. J., T. Lim, J. Ni, D. Kendall, B. Richert and A. L. Sutton. 2001. Odour, ammonia and hydrogen sulfide emissions factors for grow-finish buildings (#99-122). Final Report, National Pork Producers Council, Clive, IA.

Hendriks, J., D. Berckmans, and C. Vinckler. 1998. Field tests of bio-additives to reduce ammonia emissions from and ammonia concentration in pig houses. ASHRAE Transactions, 104(1): 1699-1705.

Hill, D. J. and C. J. Barth. 1976. Removal of gaseous ammonia and methylamine using ozone. Transactions of the ASAE, 19:935-938, 944.

Hinz, T. and S. Linke. 1998. A comprehensive experimental study of aerial pollutants in and from livestock buildings. Part 2: Results. Journal of Agricultural Engineering Research, 70:119-129.

Hobbs, P. J., B. F. Pain, R. M. Kay and P. A. Lee. 1996. Reduction of odourous compounds in fresh pig slurry by dietary control of crude protein. Journal of the Science of Food and Agriculture 71:508-514.

Hobbs, P.J. T.H. Misselbrook and T.R. Cumby. 1999. Productions and emissions of odours and gases from aging pig wasre. Journal of agricultural engineering research 72:291-298.

Hoeksma, P., N. Verdoes, and G. J. Monteny. 1993. Two options for manure treatment to reduce ammonia emissions from pig housing. Proceedings of the first international symposium on nitrogen flow in pig production and environmental consequences, EAAP Publication No. 69, pp. 301-306. Wageningen.

Hoff, J. D., D. W. Nelson and A.L. Sutton. 1981. Ammonia volatilization from liquid swine manure applied to cropland. Journal of Environmental Quality 10:90-95.

Hornig, G., M. Turk. and U. Wanka. 1999. Slurry covers to reduce ammonia emissions and odour nuisance. Journal of Agricultural Engineering Research 73:151-157.

Jacobson, L. D., S. L. Wood, D. R. Schmidt, A.J. Heber, J. R. Bicudo, and R. D. Moon. 2001. Site selection of animal operations using air quality criteria. White papers by National Center for Manure and Animal Waste Management, North Carolina State University, Raleigh, NC.

Jacobson, L.D., S.L. Wood-Gay, D.R. Schmidt, A.J. Heber, J.R. Bicudo, and R.D. Moon. 2002. Site Selection of Animal Operations Using Air Quality Criteria. White paper and Recommendations. National Center for Manure and Animal Waste Management, North Carolina State University, Raleigh, N.C. 39 p.

James, T., D. Meyers, E. Esparza, E. J. Depeters, and H. Perez-Monti. 1999. Effects of dietary nitrogen manipulation on ammonia volatilization from manure from Holstein heifers. J Dairy Sci 82:2430-9

Jongbloed, A. W. and N. P. Lenis. 1992. Alteration of nutrient as a means to reduce environmental pollution by pigs. Livestock Production Science 31:75-94.

Kaiser, S. and H. Van den Weghe. 2000. Regulatory control of nitrogen emissions in a modified deep litter system.

Karlsson S., 1996. Åtgärder för att minska ammoniakemissionserna vid lagring av stallgödsel. Measures to reduce ammonia during storage of animal manure. JTI-rapport pp 228. Jordbrukstekniska institutet. Uppsala. Sweden.

Kay, R. M. and P. A. Lee. 1997. Ammonia emissions from pig buildings and characteristics of slurry produced by pigs offered low crude protein diets. In J. A. M. Voermans and G. J. Monteney (ed) Ammonia and odour emissions from animal production facilities. Vinlelord, The Netherlands. pp. 253-259.

Keener, K.M., R.W. Bottcher, R.D. Munilla, K.E. Parbst, and G.L. Van Wicklen. 1999. Field evaluation of an indoor ozonation system for odor control. pp. 310-313 in: Proceedings of the 1999 Animal Waste Management Symposium, North Carolina State University, Raleigh, NC 27695.

Koerkamp, P. W. G., J. H. M. Metz, G. H. Uenk, V. R. Phillips, M. R. Holden, R.W. Sneath, J. L. Short, R. P.White, J. Hartung, J. Seedorf, M. Schroder, K. H. Linkert, S. Pedersen, H. Takai, J. O. Johnsen, and C.M. Wathes. 1998. Concentration and emissions of ammonia in livestock buildings in Northern Europe. Journal of Agricultural Engineering Research 70:79-85.

Kroodsma, W., J.W.H. Veld and R. Scholtens. 1993. Ammonia emission and reduction from cubicle houses by flushing. Livestock Production Science 35:293-302.

Kroodsma, W., H. C. Willers, J. W. H. Huis, and N. W. M. Ogink, 1994. Reduction of ammonia emissions from cubicle houses for cattle by slurry acidification. International Conference on Agricultural Engineering (AgEng´94), Report 94-C-028. Milano.

Kurvits, T and T. Marta. 1998. Agricultural NH3 and NOx in Canada. Environmental Pollution 102(Sl): 187-194.

Lais, S. E. Hartung and T. Jungbluth. 1997. Reduction of ammonia emissions by bioscrubber. In Proceeding of the international symposium on ammonia and odor control from animal facilities, 5330536 CIGR and EURAGENG Publication, Rosmalen. The Netherlands.

Lenis, N. P. 1989. Lower nitrogen excretion in pig husbandry by feeding: current and future possibilities. Net. J. Agric. Sci. 72:139-143.

Lim, T. T., A. J. Heber, and J. Ni. 2000. Odour setback guideline for swine production systems. In Odours and VOC. Cincinnati, Ohio, USA, 16-19 April. Water Environment Federation, Alexandria, VA, USA.

Lim, T. T., A .J. Heber, J. Q. Ni, D. C. Kendall and B. R. Richert. 2002. Effects of manure removal strategies on odour and gas emissions from swine finishing. ASAE paper No 024123.

Liu, Q., D. S. Bundy, and S. J. Hoff. 1993. Utilization ammonia concentration as odour threshold indicators for swine facilities. In proceedings of the fourth international livestock environment symposium, ASAE, St Joseph, MI.

Lorimer, J., C. Fulhage, R. Zhang, T. Funk, R. Sheffield, D. C. Sheppard and G.L. Newton. 2001.Chapter 8: Manure management strategies/technologies in (CD-Rom). National center for manure and animal waste management white papers. Ames. Iowa: Midwest Planning Services.

Malgeryd, J. 1998. Technical measures to reduce ammonia losses after spreading of animal manure. Nutrient Cycling in Agroecosystems 51:51-57.

Martens, W., M. Martinec, R. Zapirain, M. Stark, E. Hartung, and U. Palmgren. 2001. Reduction potential of microbial, odour and ammonia emissions from pig facility by biofilter. International Journal of Hygiene and Environmental Health.203: 335-345.

Martinec, M. E. Hartung, T. Jungbluth, F. Schneider and P. H. Wieser. 2001. Reduction of gas, odour and dust from swine operations with biofilters. ASAE paper No. 2001-4079.

Mattila P.K. 1998. Ammonia volatilization from cattle slurry applied to grassland as affected by slurry treatment and application technique –first year results. Nutrient cycling in agroecosystems 51: pp 47-50.

McCrory, D. F. and P. J. Hobbs. 2001. Additives to reduce ammonia and odour emissions from livestock waste: A review. J. Environ. Quality. 30:345-355.

Meisinger, J. J., A. M. Lefcourt, R. B. Thompson. 2001 Construction and Validation of Small Mobile Wind Tunnels for Studying Ammonia Volatilization. Applied Engineering in Agriculture Vol. 17(3): 375-381

Meisinger, J. J. and W. E. Jokela. 2002. Nitrogen loss measurements following field application of manure. USDA-ARS Beltsville, Maryland and Univ. Vermont, Burlington VT.

Mennen, M. G., B. G. Van Elzakkar, E. M. Van Putten, J. W. Uiterwijk, T. A. Regts, J. Van Hellemond, G. P. Wyers, R. P. Otjes, A. J. L. Verhage, and L. W. Woutters. 1996. Evaluation of automatic ammonia monitors for application in an air quality-monitoring network. Atmospheric environment. 30(19): 3239-56.

Miner, J. R.1995. An executive summary: a review of the literature on the nature and control of odour from pork production facilities. Prepared for pork national producers council. Des Moines. Iowa.

Miner. J R., and K.W. Suh. 1997. Floating permeable covers to control odour from lagoon and manure storage. Proceeding of international symposium on ammonia and odour control from animal production facilities. Vinkeloord, The Netherlands. Oct 6-10, 1997.

Misselbrook, T. H., T. J. Van der Weerden, B. F. Pain, S. C. Jarvis, B. J. Chambers, K. A. Smith, V. R. Phillips, and T. G. M Demmers, 2000. Ammonia emissions factors for UK agriculture. Atmospheric Environment, 34, 871-880.

Moal, J.F. J. Martinez, F. Guizlou and C.M. Coste.1995. Ammonia volatilization following surface applied pig and cattle slurry in France. A Agric Sci (Camb) 125: 245-253.

Moore, Jr., P. A., T. C. Daniel, D. R. Edwards, and D. M. Miller. 1995. Effect of chemical amendment on ammonia volatilization from poultry litter. J. Environ. Quality. 24:293-300.

Morken, J., and S. Sakshaug 1998. Direct Ground Injection (DGIâ) of slurry to avoid ammonia emissions. Nutrient Cycling in Agrosystems 51: 59 – 63.

Ni, J., D. Berchmans, J. Coenegrachchts, C. Vinckier, and V. Goedseels.1996. Ammonia emissions factors for swine houses with slatted floor. In Conference proceeding: International Conference on Air Pollution from Agricultural Operations. Kansas City, Missouri. Ames, IA: Mid West Plan Service. P427: 434.

Ni, J., T. T. Lim, A .J. Heber, R. Duggirala, B. L. Haymore and C. A. Diehl. 1998. Ammonia emissions from a large mechanically ventilated swine building during warm weather. ASAE Paper No. 984051.

Ni, Q., A.J. Heber, T.T. Lim, C.A. Diehl, R.K. Duggirala, B.L. Haymore and A.L. Sutton. 2000b. Ammonia emission from a large mechanically ventilated swine building during warm weather. Journal of Environmental Quality 29:751-758

Nicolai, R. E., and K. A. Janni. 1997. Development of low cost biofilter for swine production facilities. ASAE Paper No 97-4040.

Nicolai, R. E., and K. A. Janni. 1998. Biofiltration: Technology for odour reduction from swine buildings. In Proceeding of the animal production system and the environment. 327-332. July 19-22,1998. Des Monies, Iowa.

Nielsen, V.C. and B.F. Pain. 1991. Conclusions and recommendations. pp. 214 –217. In V.C. Nielson, J.H. Voorburg and P.L. Hermite (eds). Odor and ammonia emissions from livestock farming. Elsevier Applied Sciences.

Ogink, N. W. M., and W. Kroodsma.1996. Reduction of ammonia emissions from a cow cubicle house by flushing with water or a formalin solution. Journal of Agricultural Engineering Research. Vol. 63, No. 3., PP 197-204

Olivier, J. G. J., K. W. van der Hoek, J. J. M. Berdowski. 1998. Global air emissions inventories for anthropogenic sources of NO_x, NH_3 and NO_2 in 1990. Environmental Pollution 102 (S1) 135-148.

Pahl, O., A. G. Williams, R. W. Sneath, J. Goodman, L. Taylor, R. J. Dodwin and M. J. Hann. 2000. Reducing ammonia emissions from pig production-experience with oil and foam as a cover material for slurry under slats. In Conference proceeding: Second International conference on Air Pollution from Agricultural Operations. Des Moines, Iowa. P.100-107.

Pain, B. F., V. R. Phillips, C. R. Clarkson and J. V. Klarenbeek. 1989. Loss of nitrogen through ammonia volatilization during and following the application of pig or cattle slurry to grassland. Journal of the Science of Food and Agriculture 47:1-12.

Pain, B. F., and T. H. Misselbrook.1991. Relationship between odour and ammonia emissions during and following the application of slurries to land. In Odour and ammonia emissions from livestock farming. V.C. Nielsen, J. Voorbourg and P.L. Hermites (eds), Elsevier Applied Sciences, New York pp 17-21.

Pain, B. and S. Jarvis . 1999. Ammonia emissions from agriculture. In IGER Innovation. T. Gordon (ed). Cambrian Printer, Aberystwyth.

Panti, N. K., and P. Y. Jui. 1993. Effectiveness of manure additives. ASAE Paper No. 93-4201.

Paszek, D. A., L. D. Jacobson, V. J. Johnson and R. E. Nicolai. 2001. Design and management of an oil sprinkling system to control dust, odour, and gases in and from a curtain-sided pig-finishing barn. ASAE Paper No. 01-4076.

Paul, J. W., N. E. Dinn, T. Kannangara, and L. J. Fisher. 1998. Protein content in dairy cattle diets affects ammonia losses and fertilizer nitrogen value. J. Environ. Qual. 27:528-534.

Pearson, C. C., V. R. Phillips, G. Green, and I. M. Scotford. 1992. A minimum–cost biofilter for reducing aerial emissions from broiler chicken house, 245-254. In biotechniques for air pollution abatement and odour control policies. Amsterdam, The Netherlands: Elsevier Science publisher.

Phillips, V.R., B.F. Pain, C.R. Clarkson and J.V. Klarenbeek. 1990. Studies on reducing the odour and ammonia during and after the land spreading of animal slurries. Farm Buildings and Engineering 7:17-23.

Phillips, V.R., M.R. Holden, R.P. White, R.W. Sneath, T.G.M. Demmers and C.M. Wathes. 1995. Measuring and reducing gaseous and particulate air pollutants from UK livestock buildings. In Proc. Seventh International Symposium on Agricultural and Food Processing Wastes , 241-251. Chicago IL, June 18-20.

Phillips, V. R., M. R. Holden, R. W. Sneath, J. L. Short, R. P. White, J. Hartung, J. Seedorf, M. Schroder, K. H. Linkert and S. Pederson. 1998. The development of robust methods for measuring concentration and emissions rates of gases and particulate air pollutants in livestock buildings. Journal of Agricultural Engineering Research 70(1): 11-24.

Phillips, V. R., R. Scholtens, D.S. Lee, J. A. Garland and R W. Sneath. 2000. A review of methods for measuring emissions rates of ammonia from livestock buildings and slurry or manure stores, Part 1: Assessment of basic approaches. Journal of Agricultural Engineering Research 77:355-364.

Phillips, V.R., D.S. Lee, R. Scholtens, J.A. Garland and R.W. Sneath. 2001. A review of methods for measuring emission rates of ammonia from livestock buildings and slurry or manure stores, Part 2:Monitoring flux rates, concentrations and airflow rates. Journal of Agricultural Engineering Research 78:1-14.

Pitcairn, CER, I. D. Leith, L. J. Sheppard, M. A. Sutton. D. Fowler, R. C. Munro, S. Tang, D. Wilson. Hook, J. W. Erisman, S. Smeulders, and J. R. Wisniewski. (eds). 1998. Proceeding of the first international nitrogen conference. Environment pollution 102. Supp 41-48.

Priem, R. 1977. Deodorization by means of ozone. Agriculture and Environment. Elsevier Scientific Publishing Company, Amsterdam, The Netherlands. 3:227.

Quarles, C. L. and H. F. Kling. 1974. Evaluation of ammonia and infectious bronchitis vaccination stress on broiler performance and carcass quality. Poultry Sci. 53:1592-1596.

Reece, F. N., B. D. Lott and W. Deaton 1980. Ammonia in the atmosphere during brooding affects performance of broiler chicken. Poultry Sciences. 59:486-488.

Reece. F. B and D. B. Lott. 1980. The effect of ammonia and carbon dioxide during brooding on the performance of broiler chickens. Poultry Sciences. 59:1654.

Rom, H. B., F. Moller, P. J. Dahl, and M. Levring. 2000. Diet composition and modified climatic properties: means to reduce ammonia emissions in fatting pig units. In Conference proceeding: Second International conference on Air Pollution from Agricultural Operations. Des Moines, Iowa. P.384-390.

Rudek, J. 1997 Atmospheric nitrogen deposition and ecosystem health in North Carolina: A Public Perspective, Environmental Defense Fund, Raleigh NC.

Schnoor, J. L., P. S. Thorne, and W. Powers. 2001. Fate and transports of air pollutants from CAFO. Chapter 5 in Iowa concentrated animal feeding operation air quality study final report.

Schulte, D. D., D. A. Kottwitz and C. B. Gilberson. 1985. Nitrogen content of scraped swine manure. Pp 321-328. International symposium on agriculture waste, ASAE. St Joseph. MI.

Siemers, V., and H. Vanden Weghe. 1997. Biofilter/wet scrubber combination for reduction of ammonia, odour, and dust emissions of pig fattening houses. In proceeding of international symposium of ammonia and odour control from animal production facilities. Voermans, J.A.M., Monteny, G.J. Eds; ISBN: 90-901105-9-3. Vinkeloord. The Netherlands. pp537-544.

Sharpe, R. R., and Harper, L. A. 1998. Ammonia and nitrous oxide from sprinkler irrigation applications of swine effluent. J. Environ. Qual. 26:1703-1706.

Sharpe, R. R., and L. A. Harper. 1997. Atmospheric methane from a swine lagoon. pp. 237-241. In L. M. Risse (ed.) Proceedings of the southwestern sustainable animal waste management workshop. Feb. 11-13. Tifton, GA. Univ. of Georgia Publication No. ENG97-001.

Sheridan, B. A., J. G. Colligan, T. P. Curran and V.A. Dodd. 2000. Biofiltration of exhaust ventilation air from pig units. Second International Conference on Air Pollution from Agricultural Operations. Des Moines, Iowa. P.108-115.

Shi, Y., D.B. Parker, N. A. Cole, B. W. Cole, B. W. Auvermann, and J. E. Mehlhorn. 2001. Surface amendments to minimize ammonia from beef cattle feedlots. Transaction of the ASAE, 44(3): 677-682.

Small D. and S. Danish. 1999. Development of a negative air pressure cover system for swine earthen manure storage in Manitoba. A final report prepared by DGH Engineering Ltd.

Smith, K. A., D. R. Charles, and D. M. Moorhouse. 2000. Nitrogen excretion by farm livestock with respect to land spreading requirements and controlling nitrogen losses to ground and surface waters. Part 2: Pigs and poultry. Bioresource Technology 71:183-194.

Sommer, S. G., J. E. Olesen, and B. T. Christensen, 1991. Effects of temperature, wind speed and air humidity on ammonia volatilization from surface applied cattle slurry. J. Agr. Sci., Vol. 117, pp. 91-100.

Sommer, S. G. and I. K. Thomsen. 1993. Loss of nitrogen from pig slurry due to ammonia volatilization and nitrate leaching. In Proc. First International Symposium on Nitrogen Flow in Pig Production and Environmental Consequences, eds. M.W.A. Verstegen, L.A. den Hartog, G.J.M. van Kempen and J.H.M. Metz, 353-367. Wageningen: Pudoc Scientific.

Sommer, S. G. and N. Hutchings. 1995. Techniques and strategies for the reduction of ammonia emissions from agriculture. Water, Air and Soil Pollution, 85:237-248.

Sommer, S. G., E. Sibbesen, T. Nielsen, J. K.Schorring and J. E.Olse.1996. A passive flux sampler for measuring ammonia volatilization from storage facilities. J. Environ. Quality. 25:241-247.

Sommer, S. G., and O. H. Jacobsen. 1999. Infiltration of slurry liquid and volatilization of ammonia from surface applied pig slurry as affected by soil water content. Journal of Agricultural Science 132:297-303.

Stevens, R. J., R. J. Laughlin, and J. P. Frost. 1989. Effect of acidification with sulfuric acid on the volatilization of ammonia from cow and pig slurries. J. Agric. Science 113(3): 389-395.

Stowell, R. R., H. Keener, P. R. Goodrich and S. Foster.2002. Gas and odour from High-Rise™ and deep-pit swine finishing facilities. ASAE paper No 02412.

Subair, S., J. W. Fyles, and I. P. O'Halloran. 1999. Ammonia volatilization from liquid hog manure amended with paper products in the laboratory. J. Environ. Qual. 28(1): 202-207.

Sutton, A. L., K. B. Kephart, J. A. Patterson, R. Mumma, D. T. Kelly, E. Bogus, D.D. Jones, and A. J. Heber. 1996. Manipulating swine diet to reduce ammonia and odour emissions. In Conference proceeding: International conference on Air Pollution from Agricultural Operations. Kansas City, Missouri. Ames, IA: Mid West Plan Service. P445-452.

Sutton, A.L., K. B. Kephart, J. A. Patterson, R. Mumma, D. T. Kelly, E. Bogus, D. D. Jones, and A. J. Heber. 1997. Dietary manipulation to reduce ammonia and odourous compounds in excreta and anaerobic manure storage. Proceeding of international symposium on ammonia and odour control from animal production facilities. Vinkeloord, The Netherlands. Oct 6-10, 1997.

Svensson, L. 1993. Ammonia volatilization from land-spread livestock manure: Effects of factors relating to meteorology, soil/manure and application technique. Swedish University of Agricultural Sciences, Department of Agricultural Engineering. Dissertation. Uppsala.

Sweeten, J. M., R. C. Childer, and J. S. Cochran, and R. Bowler. 1991. Odour control from poultry manure composting plant using a soil filter. Applied Engineering in Agriculture 7(4): 439-449.

Swierstra, D., M. C. J. Smits, and W. Kroodsma. 1995. Ammonia emissions from cubicle houses for cattle with solid floors. Journal of Agricultural Engineering Research 62:127-132.

Swierstra, D. C. R. Braam, and M.C. Smits. 2001. Grooved Floor system for cattle housing Ammonia emissions reduction and good slip resistance. Applied Engineering in Agriculture. 17(1): 85-90.

Thompson, R. B., B. F. Pain, and Y. J. Reese.1990. Ammonia volatilization from cattle slurry following surface application to grassland. II. Influence of application rate, wind speed and applying slurry in narrow bands. Plant and Soil 125:119-128.

Turner, L. W., G. L. Cromwell, T. C. Bridge, S. Carter, and R. S. Gates. 1996. Ammonia (NH3) emissions from swine waste as influenced by diet manipulation. In Conference proceeding: International Conference on Air Pollution from Agricultural Operations. Kansas City, Missouri. Ames, IA: Mid West Plan Service. P453: 458.

Van Cauwenberghe, S., and D. Burnham. 2001. New development in amino acid and protein nutrition of poultry, as related to optimal performance and reduced nitrogen excretion. 13th European symposium poultry nutrition. Oct 2001. Blankenberge, Belgium.

Van der Molen, J., H. G. van Faassen, M.Y. Leclerc, R. Vriesema and W. J. Chardon. 1990. Ammonia volatilization from arable land after application of cattle slurry. 1. Field estimates. Netherlands Journal of Agricultural Science 38:145-158.

Van der Peet-Scwering, C. P., N, Verdoes and M. Voermans. 1997. Ammonia emissions 10% reduced with phase feeding. Swine research station Rosemalen.

Van Kempen, T. 2000. Reducing pig waste and odour through nutritional means. In livestock and poultry environmental stewardship. USDA/EPA nutritional curriculum project.

Van Kempen TA. 2001. Dietary adipic acid reduces ammonia emissions from swine J Anim Sci 79:242-7

Van't Klooster C. R. Scholtens, J. A. M. Voermans. 1996. Measurement strategies and techniques for indoors air quality in livestock building in the Netherlands. In Conference proceeding: International conference on air pollution from agricultural operations. Kansas City, Missouri. Ames, IA: Mid West Plan Service. P193: 200.

Varel, V. H. 1999. Use of Urease inhibitor to control nitrogen loss from livestock waste. Bioresource Tech. 62:11-17.

Varel, V. H., J. A. Nienaber, and H. C. Freetly.1999. Conversion of nitrogen in cattle feedlot waste with urease inhibitor. J. of Animal Sci 77:1162-8.

Vitousek, P. M., A. Aber, R.W. Howarth, G. E. Likens, P, A. Matson, D. W. Schindler, W. H. Schlesinger, and G. D. Tilman. 1997. Human alternation of global nitrogen cycle: Sources and consequences issues in ecology. Ecol. Appl. 7(3): 737-750.

Voermans, J. A. M., N. C. Verdoes, and G. M. Den Brok. 1995. The effect of pen design and climate on the emissions of ammonia from pig houses. In Conference Proceeding: 7th International Symposium on Agricultural and Food Processing Waste. 252-260, Chicago, Illinois, 18-20 June 1995. St Joseph, Mich: ASAE.

Voermans, J. A. M., N. C. Verdoes, and J. J. J. Smeets. 1996. Possibilities of ammonia reduction of sow farms. In Conference proceeding: International Conference on Air Pollution from Agricultural Operations. Kansas City, Missouri. Ames, IA: Mid West Plan Service. P119-125.

Voorburg, J.H. and W. Kroodsma. 1992. Volatile emissions of housing system for cattle . livestock production Sci. 31:57-70.

Warnek, P. 1988. Chemistry of natural atmosphere. Academic press, London.

Wathes, C. M., M. R. Holden, R. W. Sneath, R. P. White and V. R. Phillips. 1997. Concentrations and emissions rates of aerial ammonia, nitrous oxide, methane, carbon dioxide, dust and endotoxin in UK broiler and layer houses. British Poultry Science 38:14-28.

Welch, D. C., T. G. M. Demmers, J. J. Colls, and C. M. Wathes. 2001. Validation of the collection efficiency of passive ammonia flux sampler. Pp. 656-663 in livestock environment VI: Proceedings of the 6th international symposium. 21-23 may 2001. Louisville, Kentucky, USA.

Wilhelm, L. R. and D. B. Mckinney.1998. Cold weather gas level measurement in swine houses with and without pit-ventilation. ASAE paper No 98-4039.

William, A. G. and E. Nigro.1997. Covering slurry store and effect on ammonia and methane. Proceeding of international symposium on ammonia and odour control from animal production facilities. Vinkeloord, The Netherlands. Oct 6-10, 1997.

Xin, H., J. A. DeShazer and M. M. Beck. 1992. Responses of prefasted growing turkeys to acute heat exposure. Transactions of the ASAE, 35(1): 315-318.

Xue, S. K. and S. Chen. 1999. Surface oxidation for reducing ammonia and hydrogen sulfide from dairy manure storage. Transactions of the ASAE, 42(5): 1401-1408.

Zahn, J.A., A.E. Tung, B.A. Roberts and J.L. Hatfiled. 2001. Abatement of ammonia and hydrogen sulfide emissions from a swine lagoon using a polymer biocover. Journal of the Air & Waste Management Association 51:562-573.

Zhang, Y. and W. Gaakeer. 1996. A low cost lagoon cover to reduce odour emissions. In Conference proceeding: International conference on Air Pollution from Agricultural Operations. Kansas City, Missouri. Ames, IA: Mid West Plan Service. pp 395-401.

Zhang, R. H., D. L. Day, L. L. Christianson, and W. P. Jepson. 1994. A computer model for predicting ammonia release rate from swine manure pit. Journal of Agricultural Engineering Research. 58:223-229.

Zhang, Z., T. L. Richard, and D. S. Baine.1999. Effects of organic cover biofilters on odours from liquid manure storage. ASAE Paper No. 99-4087

Zhang, L., M. D. Moran, P. A. Makar, J. R. Brook and S. Gong. 2002. Modelling gaseous dry deposition in AURAMS: a unified regional air-quality modeling system. Atmospheric Environment 36(3): 537-560.

B Hydrogen Sulfide Emissions From Livestock Production

B.1 Introduction

Hydrogen sulfide (H_2S) is formed by microbial reduction of sulfate (as electron acceptor) and microbial decomposition of sulfur-containing organic compounds in manure under anaerobic and aerobic conditions according to the following equations (Arogo et al. 2000; Sawyer and McCarty 1978; Maghirang and Puma 1996).

$$SO_2- + \text{organic matter} \xrightarrow[\text{bacteria}]{\text{Anaerobic}} S_2- + H_2O + CO_2$$

$$S_2- + 2H+ \longrightarrow H_2S$$

Hydrogen sulfide in livestock buildings is mainly present in shallow barn gutters, underground or outdoor holding storage tanks, and earthen manure storage facilities.

Hydrogen sulfide is heavier than air, soluble in water, and can accumulate in underground pits and unventilated areas of livestock buildings. Ni et al. (2000, 2002a) and Heber et al. (1997) reported that H_2S concentration in swine buildings under normal operating conditions is usually very low (under 5 ppm). Levels of H_2S can be high for swine manure, compared to other animal wastes, because of the high protein content. Hydrogen sulfide is detectable as an odour at concentrations as low as 0.005 ppm. The threshold limit value (TLV), or maximum allowable concentration for humans is 10 ppm. Exposure to 200 ppm for 60 minutes will cause headaches and dizziness; 500 ppm for 30 minutes will cause severe headache, nausea, excitement, or insomnia, and it is lethal at 1000 ppm (Field 1980) The World Health Organization (WHO) recommends that exposure to hydrogen sulfide at 5 parts per billion not exceed 30 minutes.

B.2 Transport and Deposition

Hydrogen sulfide may transport in moist soils and aquatic environments because it is soluble in water. The residence time (RT) of H_2S and its reaction products is in the order of days. Residence time of hydrogen sulfide is defined as the average time that will be spent by the gas in the reservoir, between the times it enters and exits it. Residence time is calculated by dividing the reservoir size by the input (or the output). Schnoor et al. (2001) stated that the reaction of H_2S released from livestock operations is reasonably fast with a lifetime in the troposphere of 4.4 days. However, Beauchamp (1984) calculated the RT of H_2S in atmosphere to be 18 hours. Hydrogen sulfide can be transported tens or hundreds of kilometres from emission sources before being oxidized. Reacting with nitrogen oxides and ozone can oxidize H_2S in the atmosphere. This reaction would shorten the RT of H_2S in atmosphere.

$$H_2S \xrightarrow{OH\bullet} \bullet HS \xrightarrow{O_2} SO \xrightarrow[\text{or } NO_2]{O_2} S_2O$$

Hydrogen sulfide is soluble in water, where it can be oxidized very easily and could be carried for a long distance by surface water. Schnoor et al. (2001) reported that H_2S emissions for livestock operations contribute insignificant amounts to the global atmosphere and in turn is oxidized to SO_2, and then to sulfate which is deposited to lands and oceans.

B.3 Hydrogen Sulfide Measurement Techniques

Ni et al. (2002a) reported that there are only three studies available in the literature regarding the direct measurement of H_2S from swine buildings (Avery et al. 1975; Heber et al. 1997; and Ni et al. 1998). Jacobson et al. (1999) and Wood et al. (2001) reported that all the measurements of H_2S from swine buildings in Minnesota have been carried out using similar techniques. Very few research institutions are measuring H_2S from sources other than swine buildings. A Jerome Meter® is a commonly accepted instrument for measuring the concentration of H_2S. It measures the levels of H_2S in ppb ranges. Koelsch et al. (2001) monitored reduced sulfur concentrations at beef cattle feedyards using a Jerome Meter®. Other instruments are used, such as a Gas Chromatography (GC) and pulsed fluorescence SO_2 analyzer with an H_2S converter, and MDA single-point monitors

(2 to 90 ppb) (Jacobson et al. 2001), but these instruments are not as popular as the Jerome Meter®.

B.4 Hydrogen Sulfide Emissions Factors and Rates from Livestock Facilities

Hydrogen sulfide emissions factors for livestock are not available in the literature except for swine (EPA 2001). The factors for an anaerobic lagoon were calculated by using H_2S factors for swine, assuming that the pH of manure from all animal species is not different. This approach is not considered scientific. Hydrogen sulfide from poultry buildings and beef feedlots was considered insignificant (EPA 2001). Ni et al. (2002b) reported an H_2S emissions rate of 591 g d^{-1}, or 740 mg d^{-1} m^{-2} of pit surface area, or 6.3 g d^{-1} AU^{-1} from two swine finishing buildings monitored for six months. Hobbs et al. (1999) reported that H_2S rate decreased from 100 to 28 g d^{-1} at the end of 112 days of stored swine manure. Zhu et al. (2000) monitored H_2S emissions from dairy housing. They reported that the internal H_2S concentration varied during the measurement time. The emissions rate they recorded was 0.26 g H_2S/m^{-2} d^{-1}. Wood et al. (2001) reported a mean H_2S emissions rate of 1.72 µg m^{-2} s^{-1} for open lot beef facilities as compared to 14 µg m^{-2} s^{-1} for swine finishing barns in Minnesota. Schmidt et al. (2002) conducted air-monitoring studies at one turkey, one swine, and one dairy farm in Minnesota. The study concluded that H_2S emissions rates varied from 5 to nearly 550 µg $hr^{-1}m^{-2}$, compared to other published data that reported values ranging from 1,000 to 10,000 µg $hr^{-1}m^{-2}$ (Ni et al. 1998; Wood et al. 2001). Schmidt et al. (2002) attributed the differences to the difficulties in ventilation rate measurements in naturally ventilated facilities and differences in measurement and sampling methods. Bicudo et al. (2002) cited Gay et al. (2002) who have summarized H_2S flux rates from livestock and poultry manure storage units in about 40 farms in Minnesota. Mean H_2S flux rates from swine storages varied from 0.4 (manure stack) to 12.5 g H_2S m^{-2} day^{-1} (concrete storage tank). Fluxes from swine earthen basin storages varied from 0.65 to 5.1 g H_2S m^{-2} day^{-1}. Dairy manure storage values were from 0.37 (earthen basin) to 70 g H_2S m^{-2} day^{-1} (concrete storage tank).

Hydrogen sulfide emissions rates are affected by environmental and management factors. Ni et al. (2002a) reported that H_2S emissions from liquid and solid manure increase with temperature and ventilation rates. Shurson et al. (2001) cited a study by Avery et al. (1975) who reported that H_2S production in swine confinement finishing units has been shown to be highly correlated with average outside air temperature, ratio of pit area to building volume, air exchange rate for the building and daily dietary sulfur intake. The mass transfer coefficient of H_2S increases with liquid manure temperature, and higher emissions rates of H_2S are likely to occur when liquid temperature is higher than air temperature (Arogo 1997; Arogo et al. 1999; Robert et al. 2001).

Bicudo et al. (2001) showed that a natural crust seemed to be able to significantly reduce H_2S from swine manure storage. The crust also reduced H_2S concentrations in the air around the manure storage. Tengman and Goodwin (2000) reported that H_2S concentrations downwind of six deep-pit swine facilities were significantly increased during agitation and manure handling. Donham et al. (1982) and Arogo et al. (2000) found a positive correlation between the water supply sulfate concentration and the emissions rate of H_2S in under-floor pit storages in swine buildings. Koelsch et al. (2002) cite Heber and Heyne (1999) who observed that H_2S levels as measured at a property line for a wean to finish swine facility was twice as high at night than during the day. In addition, they found that high wind speeds (greater than 29 km/hr) increased emissions rates from a lagoon surface.

Bicudo et al. (2002) found that in Minnesota the continuous monitoring of ambient H_2S concentrations near swine housing and manure storages indicated that finishing facilities with earthen basin manure storages have the highest potential to exceed current Minnesota ambient H_2S standards as compared to other types of facilities and production units. Wood et al. (2001) summarized the H_2S emissions factors for different livestock raised under different management conditions (Table 1). Table 2 shows H_2S emissions factors from manure storage facilities as reported in the literature. The emissions factors listed in Tables 1 and 2 show a considerable variation as a result of the variation of prevailing environmental and management factors inside livestock buildings and manure storages. Chetner and Sasaki (2001) showed that the emissions of sulphur compounds from cattle and swine in Alberta in 2000 totalled 2,400 tonnes yr^{-1} (67% from cattle). It is important to know that their data were estimations of emissions based on calculation and many assumptions, and no emissions were actually measured.

B.5 Hydrogen Sulfide and Odour

Research to determine the relationship between hydrogen sulfide concentration and odour has produced varied results. Jacboson et al. (1997) evaluated odour and H_2S of different livestock buildings and manure storage facilities. They found a low correlation between H_2S and odour. Zhang et al. (2000) conducted a study to measure odour levels and H_2S emissions from ten hog farms in Manitoba. The study showed that there was a positive correlation between odour levels and H_2S concentrations for both swine barn exhausts and lagoon odour. Guo et al. (2000) determined a correlation coefficient, r, of 0.75 between the odour dilution threshold (DT) and H_2S concentrations for a variety of animal species, indicating that H_2S can be used as an odour indicator for some facilities. Fakhoury et al. (2000) determined a correlation coefficient, r, of 0.49 between H_2S and DT for swine manure. See the odour and air quality chapter of this report for more information.

Table 1. Hydrogen sulfide emissions rates from animal housing as reported in the literature and as conversions to units of μg m^{-2} s^{-1} for comparison Source: from Wood et al. 2001.

Species	Management	Ventilation	Location	Converted emissions rate (μg/m^2 s^{-1})	References
Dairy	Cows	Natural	Minnesota	0.18-0.97	Zhu et al. 2000
Poultry	Broiler	Mechanical	Minnesota	0.08-0.30	Zhu et al. 2000
Swine	Gestation	Mechanical	Minnesota	0.8-9.1	Zhu et al. 2000
	Farrowing	Mechanical	Minnesota	3.09-7.86	Zhu et al. 2000
	Nursery	Mechanical	Minnesota	19.8-144	Zhu et al. 2000
	Growing finishing	Mechanical	Minnesota	3.68-17.9	Zhu et al. 2000
	Growing finishing	Natural	Minnesota	4.60-17.9	Zhu et al. 2000
	Growing finishing	Mechanical	Indiana	1.9-26.9	Ni et al. 1998
	Growing finishing	Natural	Indiana	0.2-8.2	Heber et al. 1997

Table 2. Hydrogen sulfide emissions rates from manure storage as reported in the literature.

Storage type	Unit	Emissions factors	References
Deep Pit, pull plug	g m^{-2} day^{-1}	0.32	Zahn et al. 2001
Earthen, concrete-lined, steel tank	g m^{-2} day^{-1}	0.95	Zahn et al. 2001
Lagoon without photosynthetic bloom	g m^{-2} day^{-1}	0.28	Zahn et al. 2001
Lagoon with photosynthetic bloom	g m^{-2} day^{-1}	0.21	Zahn et al. 2001
Pit storage	lb yr^{-1} AU^{-1}	0.01-5.4	Jacobson et al. (2000); Ni et al. (1999); Pederson et al. (2001) Zhu et al. (2000)
Anaerobic lagoon	lb yr^{-1} AU^{-1}	0.8-9.8	Grelinger and Page (1999)
Liquid land application	lb yr^{-1} AU^{-1}	0.6	Grelinger and Page (1999)

B.6 Hydrogen Sulfide Emissions Control Strategies

There are some similarities between the techniques and abatement measures to reduce ammonia and hydrogen sulfide. The principles are the same but there are minor differences. This section will explain how these techniques are effective in reducing hydrogen sulfide emissions from livestock operations. For more detailed descriptions of these techniques, refer to the ammonia emissions control strategies section in this chapter.

B.6.1 Suppression Methods

B.6.1.1 Manure storage covers

The purpose of biological covers (biocovers), permeable, and impermeable covers is to reduce emissions of H_2S and other odorous gases. They do this in two ways: (1) physically limiting the emissions of H_2S and other gases from the surface of storage lagoons; and (2) creating a biologically active zone on top of the covers where the emitted H_2S and other gases will be aerobically decomposed by microorganisms.

Bicudo et al. (1999) conducted a pilot study to test the effect of geotextile membranes on H_2S emissions. They found that a 0.3 mm geotextile membrane with either 8 or 12 in. of straw on top was able to reduce H_2S emissions by more than 70% (Figure 1). Zhang and Gaakeer (1996) measured a 95% reduction in H_2S emissions rates by using inflated plastic covers on manure storage tanks. Xue et al. (1999) reported that covering anaerobic liquid dairy manure with 5 to 10 cm of wheat straw was effective in reducing emissions rates of hydrogen sulfide by up to 95% over a seven-week period. Miner and Pan (1995) developed a permeable blanket and or zeolite to cover manure storage. They found that this technology could reduce H_2S emissions by 90%. Zeolite volume pricing is not currently available.

A floating biological cover was evaluated for controlling odour emissions from anaerobic lagoons by Picot et al. (2001). The biological cover consisted of a peat bed, and the effects of adding ferric chloride

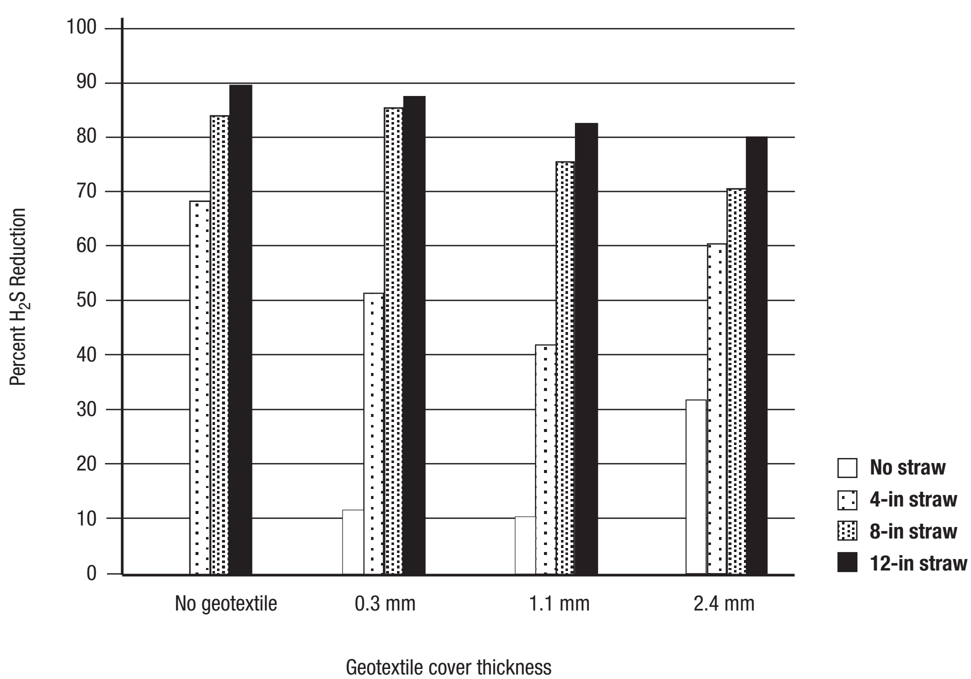

Figure 1. Percentage of hydrogen sulfide reduction by biocovers and geotextile covers *Source: Bicudo et al. 1999.*

and plants to enhance the efficiency of reduction were considered. The study was conducted in five laboratory-scale pond reactors. The pond reactors were found to represent large-scale anaerobic ponds producing H_2S. The presence of the floating peat bed significantly reduced H_2S, and emissions rate reductions were greatest in the system containing a combination of peat, Fe, and plants. Bicudo et al. (2001) showed that a natural crust seems to be able to significantly reduce H_2S from swine manure storages. The crust also reduced H_2S concentrations in the air around the manure storage.

B.6.1.2 Manure management

Heber et al. (2001) reported that flushing and pit recharge with recycled water from lagoons had major effects on emissions of H_2S. They added that frequent removal of manure from static pits significantly reduces H_2S. They also found that biweekly pit emptying had 79% less H_2S emissions compared to emptying every six weeks.

B.6.2 Inhibition Methods

B.6.2.1 Manure additives

Chemicals methods can be used to control or suppress the release of H_2S from livestock buildings and manure storage facilities. Arogo (1997) reported that the control of H_2S by chemical additives is accomplished by different procedures:

1. Addition reacts with any sulfide already present to prevent H_2S release to the air by converting the dissolved sulfide into other intermediate forms or converting the dissolved sulfide into inert metallic sulfide or converting the sulfide into bisulfide ions;
2. Addition kills sulfide-producing bacteria or changes the bacteria's environment.

Arogo (1997) stated that the chemicals used to raise the pH in order to suppress the release of H_2S could create conditions favourable to the increase of NH_3 emissions rates. Heber and Heyne (1999) tested the effect of a bacterial product (Pit Remedy™) manufactured by B&S Research (Embarrass, MN) on barn manure pits and the first-stage lagoon of a 14,600-head wean to finish swine production facility between April and September 1998. Hydrogen sulfide concentrations measured near the liquid surface at the middle of the first-stage lagoon decreased from 700 to 120 ppb between July 14 and August 12. The average H_2S concentration taken at the surface of the lagoon near the aerators decreased from 1,200 ppb on July 14, to 270 ppb on August 24. A University of Minnesota study found that the H_2S reduced by 64 to 84% by adding 8 in. Macrolite® clay balls that cost between \$2–5 US per ft^2. Stowell (2001) reported on the test conducted by Purdue University Agricultural Air Quality Laboratory on 35 manure additive products. The test revealed that several products reduce H_2S and ammonia emissions (Table 3).

Zhu et al. (1997) tested five commercial pit additives products (MCP Bio-safe, Shac, X stink, CPPD). The study did not show any reduction in H_2S emissions by applying these products to swine manure.

Ritter et al. (1975) found that hydrogen peroxide was effective in reducing 100 ppm of H_2S in liquid dairy manure in two hours. Chen and Xue (1998) used 0.5% of hydrogen peroxide and/or potassium permanganate on an anaerobic dairy liquid manure lagoon. They found the addition of both hydrogen peroxide and potassium permanganate reduced the concentration and emissions rate of hydrogen sulfide by 80% over five weeks, but Miner (1995) reported that hydrogen peroxide and potassium permanganate are expensive and dangerous to handle. Miner (1980) reported that the addition of lime to raise the manure pH above 9.5 would decrease H_2S emissions substantially. Day (1966) reported that raising manure's pH to 9.5 by addition of lime would completely eliminate the escape of hydrogen sulfide from manure.

B.6.2.2 Diet manipulation

Diet manipulation can be very effective in reducing H_2S. Kendall et al. (1999) reported that reducing crude protein (CP) by 4.5% and adding synthetic amino acids to pig diets can reduce H_2S emissions by 40%. Kendall et al. (1999) also found that reducing the dietary CP by 2.7% and adding 10% soybean hulls to diets lowered aerial H_2S levels by 26.5%. Hill et al. (2001) reported that addition of 10% of soybean hull with 3.4% fat to corn-soybean meal could reduce H_2S emissions by 32%. Sharson et al. (1998) showed that a reduction in H_2S could be achieved by feeding nursery pigs a lower sulfur diet compared to traditional diets. Gao et al. (2002) proved that adding at least 1.2% of diatomaceous earth and 0.6% of zeolite to a regular corn and soybean meal-based grower diet at any tested levels did not affect H_2S emissions from swine manure. Some researchers (Kerr and Easter, 1995) found that pigs fed reduced CP had similar growth performance to those fed control diet. Other

Table 3. Manure additives tests conducted by Purdue University *Source: Stowell, 2001*.

Product	Decrease H_2S	Decrease NH_3		
	Decrease %	**Certainty %**	**Decrease %**	**Certainty %**
Agri-Clean				
Agricycle™			3%	75%
AgriKlenz Plus			6%	95%
Alken Clear-Flo®	47%	95%		
AWL-80			10%	95%
Biocharge Dry			7%	95%
Biological Manure Treatment			5%	95%
BIO-MAX Biosystem				
Conserve-N				
Digest 54 Plus			2%	75%
EM Waste Treatment			15%	95%
GT-1000OC & BC-2000AF	34%	95%		
INHIBODOUR®	36%	95%		
KOPROS®				
Krystal Air™			7%	95%
Lagoon Aid				
Manure Management Plus™			6%	95%
MBA-S	19%	75%	3%	75%
MICROBE-LIFT				
MUNOX®				
M2 Acid Buffer				
Nature's Key Pit & Lagoon Treatment™				
N-P 50			3%	75%
OdourKlenz BMT				
Peroxy Odour Control			3%	95%
Pit Remedy				
PS1	14%	75%		
Roebic Manure Liquefier				
Roebic Odour Eliminator	23%	95%		
SEPTI-SOL				
Solmar AW-509				
Super Microbial Odour Control (SMOC)	37%	95%		
UC-40™ Microbe Formula	15%	75%		
X12				
Zymplex	27%	95%		

researchers (Tuitoek et al. 1997) reported a decrease in the growth rate of pigs fed reduced CP.

B.6.3 Capture and Control Methods

B.6.3.1 Oil sprinkling

Jacobson et al. (1998) reported that a daily sprinkling of vegetable oil at a rate of 0.5 mL ft^2 has been found to reduce the H_2S emissions by up to 60%. Zhang et al. (1997) observed 30% reduction of H_2S and ammonia NH_3 concentrations with canola oil sprinkling. The same results were obtained in a study conducted at Prairie Swine Centre in Saskatchewan (Lemay 1999), but Godbout et al. (2001) reported that these results could not be verified because oil sprinkling did not affect H_2S during an experiment they conducted.

B.6.3.2 Biofiltration

Biofiltration is an effective method for reducing the emissions of H_2S, odour and NH_3 from livestock buildings (Nicolai and Janni, 1997, 1998). Biofilters usually consist of ventilation fans that exhaust air from the building through ducts into a plenum below the biofilter media. The air passes through the biofilter media where the microorganisms treat it before it is emitted into the atmosphere.

A study by Nicolai and Janni (1997) reported that in gestation/farrowing H_2S was reduced by 90% using a biofilter. Another study by Turgeon (1997) found that H_2S emissions were reduced by 96% when exhaust air from a livestock building passed through a biofilter. Dombroski et al. (1994) found that a biofilter filled with coarse sphagnum peat and inoculated with *Thiobacillus thiooxidens* and *Thiobacillus thoparus* reduced H_2S by 99.9%. DeBruyn (2000) conducted an experiment in Manitoba to evaluate the efficiency of biolfiters in removing odorous gases from livestock buildings. They found that H_2S was completely eliminated from almost every sample of biofilter exhaust air.

Sun et al. (2000) found that a compost/wood chip biofilter removed 47-94% of H_2S. They also noticed that the removal efficiency of the H_2S depends on the moisture content of the media and the retention time of the gas. Shojaosadati and Elyasi (1999) reported that H_2S was efficiently removed from contaminated air by a pilot-scale compost biofilter. Sludge, from the leather industry, was inoculated into spent mushroom compost, mixed with grounded snail shell (GSS) (shell:compost, 1:5), which was used for a buffering bed against a pH decline during the operation. More than 99% of the H_2S was removed from the H_2S loaded air.

A study conducted by Zarook et al. (2002) in Ontario to test the efficiency of a BIOSORBENS‰ media filled biofilter in removing H_2S. They operated two identical laboratory pilot BIOSORBENS‰ media filled biofilters for six months. They found a removal efficiency of more than 99% H_2S at a concentration level of about 40 ppm at 30-second empty bed residence times could be achieved.

B.6.3.3 Bioscrubbing

The concept of bioscrubbing is similar to biofiltration. Both rely on the microbial degradation of H_2S. The difference between bioscrubbing and biofiltration is that the bioscrubber is housed in a closed tower containing water. Nishimura and Yoda (1997) used a bioscrubber to remove H_2S from biogas generated from the anaerobic digestion of wastewater. They found H_2S in biogas was effectively reduced from 2000 ppm to less than 20 ppm by using bioscrubbers. A laboratory-scale fixed-film bioscrubber was set up in Singapore and evaluated in terms of its use in removing H_2S during wastewater treatment (Koe and Yang 2000). The influent H_2S concentration was approximately 5 ppm. Results showed that when the gas retention times were reduced from 5 seconds to 4 and 3 seconds, removal efficiency decreased to 78 and 68%, respectively. The maximum practical elimination capacity of the system was determined to be approximately 90 g H_2S m^{-3} h^{-1}, and the maximum elimination rate was 120 g H_2S m^{-3} h^{-1}.

B.6.3.4 Activated carbon

Marquot and Hendricks (2002) reported that activated carbons are especially effective in removing H_2S and organic odorous compounds in wastewater treatment plants. Adsorption capacities of activated carbons for H_2S vary from 2 to 300 mg H_2S g^{-1} activated carbon, depending on the type of carbon (Bagreev et al. 2001).

B.6.3.5 Ozone

Masuda et al. (2001), Fitament et al. (2000) and Von Bernuth (2001) reported that using ozone can help increase the removal of H_2S from the air of swine buildings. Goodrich et al. (2001) reported on the results of a pilot study in full scale finishing barns in Minnesota. The study showed that ozone air treatment reduced H_2S by 33% in the cold weather season but not during warmer months. A study was conducted at Michigan State University to evaluate the effectiveness of the application of ozone to swine manure. They found that H_2S concentration was slightly reduced by applying ozone to manure.

B.6.3.6 Non-thermal plasma

Non-thermal plasmas are highly reactive radicals, atoms, plasma electrons, and ions generated by an electrical discharge in the air. These plasma species can react with odorous and toxic gases emitted from manure and convert these gases into non-odorous and non-toxic, or easily managed compounds (Ruan 2000). Goodrich and Wang (2002) developed and tested a prototype non-thermal plasma reactor with a special configuration of wire-to-plate geometry. They found the designed reactor is highly efficient in removing H_2S at the specified flow rate of 5.7 m^3 min^{-1}. Field test results show that at a 5.7 m^3 min^{-1} flow, for H_2S with an initial concentration less than 50 ppm, the removal efficiency achieved was more than 95%. Ruan et al. (1997) reported a 100% removal efficiency of 60 ppm H_2S by using a corona plasma reactor.

B.7 Hydrogen Sulfide and Safety Consideration

McAllister and McQuitty (1965) and Donham et al. (1982) reported that H_2S could be produced in a short period of time in livestock buildings. Workers may occupationally be exposed to hazardous levels of H_2S from manure (Morse 1981). They could be exposed to H_2S during the agitation of manure, when entering under barn manure storage to fix equipment, or when they accidentally fall in manure pits. Hydrogen sulfide is accountable for most manure-related deaths in both humans and animals (Lorimor, 1994). A study was conducted in Saskatchewan by Chénard et al. (2002) to assess the H_2S exposure risks of workers while performing specific manure management tasks in swine operations. They found that plug pulling could generate high concentrations of H_2S. In some cases the maximum recorded in some events monitored reached 1,000 ppm. As noted above, the threshold limit value (TLV) or maximum allowable concentration for humans is 10 ppm. Exposure to 200 ppm for 60 minutes will cause headaches and dizziness; 500 ppm for 30 minutes will cause severe headache, nausea, excitement, or insomnia. High concentrations of 800 to 1,000 ppm cause immediate unconsciousness and death through respiratory paralysis, unless the victim is moved to fresh air and artificial respiration is immediately applied (Ohio Extension 1998). Approximately three deaths in swine confinement workers have been reported from exposure to H_2S in Alberta from 1996–2000. Also, high levels of H_2S can negatively affect animal health. Chapin et al. (1998) reported that swine living under the condition of 20 ppm of H_2S could demonstrate fear of light and loss of appetite.

The following are the best management practices recommended to avoid the danger or eliminate the release of H_2S as compiled by the Farm Safety Association and Saskatchewan Department of Labour.

1. Under no circumstances should anyone enter a liquid manure pit without wearing a self-contained breathing apparatus, even if the pit is empty. Use a lifeline that is connected to someone outside the danger area.
2. Never allow the manure pit to fill completely. Allow 1 to 2 feet of air space to accommodate concentrations of gas.
3. If possible, lower the level of liquid manure in the storage facility before commencing agitation. This will further reduce the possibility of gas being forced above floor level.
4. Keep the agitator below the liquid surface. Gas will be released in greater volumes if vigorous surface agitation occurs.
5. Provide strong ventilation during pumping and agitation. The building interior should be off limits to people, and if possible, animals should be evacuated.
6. Because of the dangers presented by the agitation and pumping operations, these procedures should involve two people, connected by a lifeline, with one person always outside of the danger area.

B.8 References

Arogo, J. 1997. Hydrogen sulfide emissions and control parameters from stored liquid manure. PhD dissertation. Department of agricultural engineering. University of Illinois at Urbana-Champaign.

Arogo, J., R. H. Zhang, G. L. Riskowski, and D. L. Day. 1999. Mass transfer coefficient for hydrogen sulfide emissions from aqueous solutions and liquid swine manure. Transactions of the American Society of Agricultural Engineers. 42(5): 1455-1462.

Arogo, J., R. H. Zhang, G. L. Riskowski, D. L. Day. 2000. Hydrogen sulfide production from stored liquid swine manure: a laboratory study. Transactions of the ASAE, 43(5): 1241-1245.

Avery, G. L., G. E. Merva and J. B. Garrish. 1975. Hydrogen sulfide production in swine confinement units. Trans. Am. Soc. Agric. Engrs. 18:149-151.

Bagreev, A., F. Adib, F. and T. J. Bandosz, T.J. 2001. pH of activated carbon surface as an indication of its suitability for H_2S removal from moist air streams. Carbon, 39: 1897-1905.

Banhazi.T and C. Cargill. 2000. Reducing odour and pollutant emissions from piggery buildings. www.sardi.sa.gov.au/pages/livestock/pigs/pub/news/

Beaucham. RO., J.S. Bus. J.A. Boreikocj and D.A. Andjelkovich. 1984. A critical review of the literature on Hydrogen sulfide toxicity. CRC Critical Review in Toxicology 13(1) 25-57.

Bicudo, J. R., D. R. Schmidt, C. L. Tengman, W. Powers, L. D. Jacobson, and C. J. Clanton. 2001. Odour and gas from a naturally crusted swine manure storage. ASAE Paper No. 02-4059.

Bicudo, J. R., C. L. Tengman, L.D. Jacboson, L. D. Jacobson. 2002. Ambient H_2S concentrations near swine barns and manure storages.

Chen, S., Xue, S. K., 1998. Optimizing the anaerobic processes for treating animal Wastewater. Animal Production Systems and the Environment, An International Conference or Odor, Water Quality, Nutrient Management and Socioeconomic Issues, Volume II, page 741-746. July 19-22, 1998.Des Moines, Iowa.

Chetner, S. and D. Sasaki.2001. Agricultural air emissions inventory for Alberta. Literature review prepared for intensive livestock operations working group.

Day, D.L. 1966. Liquid hog manure can be deodourized by treatment with Chlorine or lime. Illinois Research (Summer) 127-16.

Donham, K. J. and K. E. Gustafson. 1982. Human occupational hazards from swine confinement. Annals, American Conference of Governmental Industrial Hygienists, 2, 137-42.

Dombroski. E.C., I.D. Gaudet, and R.N. Coleman. 1995. Reduction of odorous and toxic from Kraft pulp mills using biofilter, pp 287-294, Conference on biofilteration, an air pollution control technology, Los Angeles: University of Southern California.

EPA. (U.S. Environmental Protection Agency). 2001. Emissions from animal feeding operations (Draft).

Fakhoury, K. J., A. J. Heber, P. Shao and J. Q. Ni. 2000. Correlation of odour detection thresholds with concentrations of hydrogen sulfide, ammonia and trace gases emitted from swine manure. ASAE Paper No. 00-4047.

Field B. 1980. Rural health and safety guide: Beware of on-farm manure storage hazards, volume S-82. West Lafayette, in cooperative extension service, Purdue University.

Fitament, D., N. Guingand, A. Laplanche, and D. Delzescaux. 2000. A Study of a procedure to deodourise from piggeries with ozone. Journees Rech Porcine en France. 32: 67-75.

Gay, S.W., C.J. Clanton, D.R. Schmidt, K.A. Janni, L.D. Jacobson, and S. Weisberg. 2002. Odor, total reduced sulfur, and ammonia emissions from livestock and poultry buildings and manure storage units. ASAE Applied Engineering in Agriculture

Goodrich. P. R. and Y. Wang. 2002. Nonthermal Plasma treatment of swine housing gases. ASAE Paper No 024196.

Godbout, S., S.P. Lemay, R. Joncas, J.P. Larouche, D.Y. Martin, J.F. Bernier, R.T. Zijlstra, L. Cherd, A. Marquis, E.M. Barber and D. Masse.2001 Oil Sprinkling and Dietary Manipulation to Reduce Odour and Gas Emissions from Swine Buildings Laboratory Scale Experiment. Pp. 671-678 in Livestock Environment VI: Proceedings of the 6th International Symposium (21-23 May, Louisville, Kentucky, USA) ed. Richard R. Stowell, Ray Bucklin, and Robert W. Bottcher. ,Pub. Date 21 May 2001 . ASAE Pub #701P0201

Grelinger, M. A. and A. Page. 1999. Air pollutant emissions factors for swine facilities. pp 398-408 in air and waste management conference proceeding Oct 26-28, 1999.

Guo, H., L. D. Jacobson, D. R. Schmidt and R. E. Nicolai. 2000. Correlation of odour dilution threshold and H_2S and NH_3 concentrations for animal feedlots. ASAE Paper No. 00-4043.

Heber, A. J., R. K. Duggirala, J. Q. Ni, M.I. Spence, D. S. Bundy, A. Sutton, D. T. Kelly and K.M. Keener. 1997. Manure treatment to reduce gas emissions from large swine houses. In proceeding of international symposium on ammonia and odour control from animal production facilities. Vinkeloord, The Netherlands. Oct 6-10, 1997.

Heber, A. J., T. Lim, J. Ni, D. Kendall, B. Richert and A. Sutton. 2001. Odour, ammonia and hydrogen sulfide emissions factors for grow to finish buildings. A final report submitted to National Pork Producers' Council. Clive, Iowa.

Heber, A. J., M. J. Heyne. 1999. Outdoor hydrogen sulfide concentrations near a swine feeding facility. ASAE Paper No. 99-4006.

Hobbs, P. J., T. H. Misselbrook and T. R. Cumby.1999. Production and emissions of odour and gases from aging pig waste. Journal of Agricultural Engineering Research. 72:291-298.

Jacobson, L. D., L. D., C. L. Clanton, C. Radman, D. Schmidt, R.Nicolai, and K.A. Janni.1997. Comparison of hydrogen sulfide and odour emissions from animal manure emissions. pp.404-412. Proceeding of international symposium on ammonia and odour control from animal production facilities. Vinkeloord, The Netherlands. Oct 6-10, 1997.

Jacobson, L. D., B. Hetcher, K. A. Janni and L. J. Johnston. 1998. Odor and Gas Reduction from Sprinkling Soybean Oil in a Pig Nursery. Presented at the 1998 ASAE Annual Inter. Meeting in Orlando, FL., St. Joseph, MI. USA.

Jacobson, L.D. and others. 1999. Literature review for air quality and odour. Topic IIIH of generic environmental impact statement prepared for the Minnesota Environmental Quality Board.

Jacobson, L.D., J. R. Bicudo. K. A Janni, D. R. Schmidt, and C. L. Tengman, 2000. Chronic odour and H_2S emissions rates from animal production facilities and manure storage units. Ag. Eng. 2000, Warwick, UK, July 2-7.

Jacobson, L., J. Lorimor, J. Bicudo, and D. Schmidt. 2001. Emissions from animal production. Lesson 40 of livestock and poultry environmental stewardship curriculum. MWPS, Ames, IA. 29 pages.

Kendall, D. C., B. T. Richer, A. L. Sutton, J. W. Frank, S. A. DeCamp, K. A. Bowers, D. Kelly, and M. Cobb. 1999. Effects of fiber addition (10% Soybean Hulls) to a reduced crude protein diet supplemented with synthetic amino acids versus a standard commercial diet on pig performance, pit composition, odour and ammonia levels in swine buildings. Journal of Animal Science. 77 (Suppl): 176. (Abstract).

Kerr, B.J. and R.A. Easter. 1995. Effect of feeding reduced protein, amino acids-supplemented diets on nitrogen and energy balance in grower pigs. J. Animal Sciences.73: 3000-3008.

Koe, L. C. C.; F. Yang. 2000 Bioscrubber for hydrogen sulfide removal water. Sci Technol v 41, No. 6, pp141 (5).

Koelsch, K B. L. Woodbury, D. E. Stenberg D. N. Miller, D. D. Schulte. 2002. Survey of hydrogen sulfide concentrations in vicinity of beef cattle feedlots. ASAE Paper No 02-4088.

Maghirang, R.G. and M.C. Puma .1996. Airborne and settled dust in a swine house. ASHRAE transaction. (9): 126-130.

Masuda, J., J. Fukuyama, and S. Fujii. 2001. Ozone injection into an activated carbon bed to remove hydrogen sulfide in the presence of concurrent substrates. J. Air Waste Manage. Assoc. 51 (5): 750-755.

McAllister, J. S. V., and J. B. McQuitty. 1965. Release of gases from slurry. Rec. Agr. Res. 14(2): 73-78. Ministry of Agriculture, Northern Ireland.

Miner, J. R. 1980. Controlling odour from livestock production facilities. State of the Art. In livestock waste: A renewable resource proc. 4th international symposium on livestock waste.

Miner, J. R.1995. An executive summary: a review of the literature on the nature and control of odour from pork production facilities. Prepared for pork national producers council. Des Moines. Iowa.

Morse, DL., M.A. Woodbury . K. Rentmeester. 1981. Death caused by fermenting manure. JAMA. 245: 63:64.

Ni, J. Q., A. J. Heber, T. T. Lim, R. Duggirala, B. L. Haymore, C. A. Diehl, and A. L. Sutton. 1998. Hydrogen sulfide from a large mechanically ventilated swine building during warm weather.

Ni, J. Q., A. J. Heber, T. T. Lim, B. L. Haymore, and C. A. Diehl. 1999. Continuous measurement of hydrogen sulfide emissions from two large swine finishing buildings. ASAE Paper No. 99-4132.

Ni, J. Q., A. J. Heber, K. J. Fakhoury, P. Shao, A. L. Sutton, D. Kelly, J. A. Patterson and S.T. Kim. 2000. Laboratory measurement of hydrogen sulfide and sulfur dioxide release from swine manure of different solid contents. ASAE Paper No. 00-4082.

Ni, J. Q., A. J. Heber. C. A. Diehl, T. T. Li, R. K. Duggirala and B. L. Haymore. 2002a. Summertime concentration and emissions of hydrogen sulfide at mechanically ventilated swine finishing building. Transaction of ASAE, 45(1): 193-199.

Ni, J. Q., A. J. Heber, T. T. Lim, and C. A. Diehl. 2002b. Continuous measurement of hydrogen sulfide emissions from two large swine finishing buildings. Journal of Agricultural Science 138(2): 227-236.

Nicolai, R.E. and K.A. Janni.1997. Development of a low cost biofilter for swine production. ASAE paper No 97-4040.

Nicolai, R.E. and K.A. Janni.1998. Comparisons of biofilter retention time. ASAE paper 98-4053.

Nishimura, S. and M. Yoda. 1997. Removal of hydrogen sulfide from anaerobic biogas using bioscrubber. Water science and technology. 36(6-7): 349-356.

Picot, B; J. Paing, L Toffoletto, J. P. Sambuco, R. H. R. Costa. 2001. Odour control of an anaerobic lagoon with a biological cover: Floating peat beds. Water Sci Technol v 44, n9, pp309

Ritter, W. F., N. E. Collins, and R. P. Eastburn. 1975. Chemical treatment of liquid dairy manure to reduce malodours. In: Managing Livestock Wastes. Proceedings of the 3rd International Symposium on Livestock Wastes. ASAE: St. Joseph, MI. pp. pp. 381-384.

Robert, M. J., R. A. Aherin, and Y. Zhang. 2001. Reducing fatality risks from livestock manure storage facilities pp. 394-401 in Livestock Environment VI: Proceedings of the 6th International Symposium (May 21-23, Louisville, Kentucky, USA) ed. Richard R. Stowell, Ray Bucklin, and Robert W. Bottcher, Pub. Date 21 May 2001. ASAE Pub #701P0201.

Ruan, R., P. Chen, A. Ning, S. Deng, H. Ma, Y. Wang, and P. Goodrich. 2000. Non-thermal plasma reactor for decomposition of odorous gases. U.S. Patent Pending.

Sawyer, C. N. and P. L. McCarty, 1978. Chemistry for Environmental Engineering, 3rd Edition. McGraw-Hill Book Company, New York, NY. pp 532.

Schmidt, D. R., L D. Jacobson, K.A Janni. 2002. Continuous monitoring of ammonia, hydrogen sulfide and dust from swine, dairy and poultry barns. ASAE paper No 024059

Schnoor, J. L., P. S. Thorne and W. Powers. 2001. Fate and transports of air pollutants from CAFO. Chapter 5 in Iowa concentrated animal feeding operation air quality study final report.

Shojaosadati, S., and A. S. Elyasi 1999. Removal of hydrogen sulfide by the compost biofilter with sludge of leather industry. Resources Conservation and Recycling, 27(1-2): 139-144.

Stowell. R. 2001. Ammonia Emissions and Hydrogen Sulfide Levels during Handling of Manure-Laden Drying Bed Material in a High-Rise™ Hog Facility. ASAE Paper No: 014093

Sun, Y. C.J. Clanton, K.A. Janni and G.L. Malzer. 2000. Sulfur and nitrogen balances in biofilters for odourus gas emissions control. Transaction of ASAE, 43(6): 1861-1875.

Tengman, C. L., and R. N. Goodwin. 2000. Hydrogen sulfide concentrations downwind from agitated swine manure pits, ASAE Paper 00-4078.

Tuitoek, K. L.G. Young, C.F.M de Lange and B.J. Kerr. 1997. The effect of reducing excess amino acids on growing-finishing pig performance: An evaluation of the ideal protein concept. Journal of Animal Sciences. 75:1575-1583.

Von Bernuth, 2000. Impact of odour and dust on pig performance. National Pork Producers Council. NPPC Report No. 00-065. Des Moines, IA. NPPC.

Wood, S. L., K. A. Janni, C. J. Clanton, D. R. Schmidt, L. D. Jacobson and S. Weisberg. 2001. Odours and Air from Animal Production Systems. ASAE Paper No. 01-4043.

Zahn, J.A.; A.E. Tung, B.A. Roberts, Hatfield, J.L. "Abatement of Ammonia and Hydrogen Sulfide Emissions from a Swine Lagoon Using a Polymer Biocover," J. Air & Waste Management Assn. 2001 51,562-573.

Zhu, J., D. S. Bundy, X. Li, and N. Rashid. 1997. Controlling odour and volatile substances in liquid hog manure by amendment. Journal of Environmental Quality 26:740-743.

Zhu, J., L. Jacobson, D. Schmidt, and R. Nicolai. 2000. Daily variations in odour and gas from animal facilities. Transactions of the ASAE, 16(2): 153-58.

C Research Gaps Related to Ammonia and Hydrogen Sulfide Emissions

C.1. Research and Development Gaps

Technology

Research studies in swine and poultry have shown that there is a potential for reducing ammonia and hydrogen sulfide from manure by diet manipulation. However additional research is required to evaluate the effectiveness of diet manipulation techniques since the results of these studies are inconsistent. Also additional research is needed to determine if diet manipulation can adversely affect the health and productivity of the livestock.

Some mitigation techniques to control the emissions of one pollutant might lead to generation of another pollutant such as lowering pH of manure by adding some chemicals to reduce ammonia emission will result in increasing hydrogen sulfide emissions from manure. So better knowledge of how different emissions control methods for different pollutants interact is needed.

There are conflicting research results about the efficacy of manure additives in reducing ammonia and hydrogen sulfide. Individual products must be carefully evaluated.

There are many emissions control technologies, but little effort has been made to develop specific economic models that would generate benefit-cost analysis and predict outcomes of using different emissions control technologies. Developing economic models to assess each technology for costs and benefits is a necessity.

Emissions rates estimation

There is a need for accurate ammonia and hydrogen sulfide emissions factors calculations from confined feeding operations (CFOs) in Alberta. The current emissions factors for CFOs in Alberta are not representing the Alberta situation. Ammonia and hydrogen sulfide emissions rates should be determined in relation to manure production, storage, handling, processing and application practices that are commonly used in Alberta. Different research organizations in Alberta should initiate a coordinated research program to develop a scientifically sound basis for estimation and measurements of ammonia and hydrogen sulfide emissions from CFOs on a provincial scale. The prioritization and the importance of the ammonia and hydrogen sulfide emissions from CFOs research should be based on policy and health effect. The accuracy and precision of ammonia and hydrogen sulfide measurement techniques should be determined. Standardized sampling protocols for ammonia and hydrogen sulfide should be developed and implemented. Research is also needed to increase understanding of the factors that influence rates of ammonia and hydrogen sulfide emissions, which will aid the development of predictive models.

Health issues

Limited research has been conducted to determine the health effects of ammonia and hydrogen sulfide for residents living near CFOs. Comprehensive research to determine the potential relationships between emissions constituents, concentrations, and potential health indicators, and devising appropriate control strategies accordingly are of high priority. Exposure assessment research is required to elucidate the relationship of reported symptoms among CFO neighbours and emissions from CFOs. Acceptability criteria for community–level exposure to ammonia and hydrogen sulfide and other odorous gases should be devised and implemented. There is also a need to establish exposure standards for workers who spend an extended time working inside confined livestock buildings.

Modeling

Fast, accurate predictive modeling has become a critical tool for directing environmental policy and regulations. AAFRD and NRCB are pursuing odour dispersion modeling to simulate the dispersion of odour from CFOs in Alberta for developing a Minimum Distance Separation (MDS). Since the relationship between ammonia and odour from CFOs cannot always be correlated, therefore, dispersion modeling of ammonia from CFOs is also needed to ensure compliance with ambient ammonia concentrations.

Extension and technology transfer

Educational programs to inform and encourage adoption of cost-effective gaseous emissions control technology are immediate needs. These programs should be effectively delivered to CFO producers by inventing practical ways, capable of widespread adoption, of reducing ammonia and other gases from CFOs. The demonstrations of ammonia and hydrogen sulfide mitigation on a commercial scale are necessary to prove to producers these techniques are technologically and economically feasible.

C.2 Key Research Gaps

The four priority areas for further research related to ammonia and hydrogen sulfide are:

- Develop and validate models for calculation of ammonia and hydrogen sulfide emissions from housing, manure storage and treatment, and land application of manure for cattle operations in Alberta.
- Assess the health effects and impacts of ammonia and hydrogen sulfide on workers and residents living near CFOs.
- Determine if oil sprinkling techniques can consistently reduce ammonia and hydrogen sulfide emissions from swine facilities in Alberta.
- Develop effective technology transfer tools that help CFO producers to adopt appropriate and economically feasible ammonia and hydrogen sulfide control technologies (diet manipulation and manure storage).

D Beneficial Management Practices for Ammonia and Hydrogen Sulfide

From the review of the literature, different beneficial management practices (BMPs) have been developed to reduce the level of ammonia and hydrogen sulfide from the storage, handling, and use of manure. BMPs were organized into five management categories:

1. Feed management;
2. Manure storage;
3. Building hygiene;
4. Manure additives; and
5. Manure application.

D.1 Feed Management

Feeding management strategies can influence the efficiency of nutrient utilization in livestock operations, resulting in less unused nutrients leaving the animal. Diet manipulation is considered the most efficient and economical way to control excess nutrient excretion.

Feed management includes:

- Reducing the dietary crude protein level and supplementing with synthetic amino acids;
- Changing the carbohydrate structure in the diet to increase bacterial utilization of nitrogen;
- Enzymes added to diets to improve nutrient utilization;
- Zeolite is another feed additive, which shows promise in feedlots;

- Spilt sex feeding and multi-phase feeding, whereby feed composition is much better matched to the needs of different animals and growth stages. By adjusting the nutrient supply to suit the needs of animals, less waste is produced.

Benefits

- Reduction of nitrogen excretion and ammonia without affecting productivity. Research has shown feeding the ideal protein with a desired balance of amino acids could reduce the N excretion by up to 40%. Kay and Lee (1997) found an 11% decrease in manure volume for each 1% reduction of the pig's dietary crude protein.
- Improved feed composition (e.g. higher quantities of limiting amino acids enhance N uptake of nitrogen from feed). Feeds can be combined to create the desired balance of amino acids, or feeds can be supplemented with lysine and the other limiting amino acids.
- Reduction of ammonia emission. With the addition of non-starch polysaccharides, fermentation leads to the conversion of ammonia to bacterial protein and results in a lowering of excreta pH, both factors that lower ammonia emission.
- Reduction of ammonia emission can be delayed through a reduction of excreta pH. Excreta pH is a function of the acid-base balance of the feed and can also be lowered through the use of feed additives such as benzoic, adipic, or phosphoric acid. Phosphoric acid can be used as the phosphorus source in animal diets with a secondary benefit of reducing urine pH. Some experiments have shown reductions in ammonia emission around 30% with this technique.
- H_2S reduction without sacrificing pig performance. By carefully selecting low sulfur feed ingredients and using them to formulate nutritionally adequate, low sulfur starter diets, total sulfur and sulfate excretion can be reduced by approximately 30% without compromising energy and nitrogen digestibility or pig performance. Sulphate level in drinking water is a significant contributor to hydrogen sulfide levels in commercial swine farms, so water testing is necessary to assure that levels of sulphate are not high (Shurson et al. 2000).
- Decreased feed costs. Dutch research has shown that a three-phase feeding program can reduce ammonia 45%. Increasing the number of feed phases has been proven to decrease feed cost as well as reduce urine excretion and ammonia without compromising the performance of the animal.

What Can the Producer Do?

Swine

- Select animals for their feed efficiency conversion and appropriate use of certain processing and feeding methods.
- Use high-quality protein sources with superior amino acid balance and formulate diets to achieve an ideal protein balance.
- Feed pigs low crude protein diets that meet the requirements of the animal for essential amino acids (the building blocks of protein), through the addition of synthetic amino acids. This allows formulation of rations that contain a lower crude protein content than is commonly fed.
- Use some feed ingredients that have higher fiber characteristics that may be effective in shifting nitrogen excretion away from urine and toward feces. If more nitrogen is excreted in the feces, it is in a chemical form more resistant to volatilization.
- Work with nutritionist.

Dairy cattle

- Feed low rumen-degradable protein. Rumen-degradable proteins are the proteins that are fermented in the rumen and are therefore only useful to the rumen bacteria, that is, the rumen degradable protein is used by the bacteria to grow. The cow then digests the bacteria as her main source of protein. Canola and soybean meal provide mostly rumen degradable protein whereas distillers grains, corn gluten meal and blood meal provide mostly rumen by-pass protein (that is, rumen undegradable protein).
- Use protein supplements to allow the cow's degradable and undegradable protein requirements to be met without overfeeding crude protein. The most common protein supplements are: canola meal, soybean meal, distillers grains, corn gluten meal and blood meal.

- Follow feeding sequence, feeding frequency and grouping strategy. Use of Total Mixed Rations (TMR) is becoming the most common feeding method. In a TMR, all of the feeds are mixed together. TMR's are mixed and fed once or twice daily. Common grouping strategies are: (1). a single group TMR, where the same ration is fed to all of the milking cows for the entire lactation, (2). early lactation and late lactation groups, or early, mid and late lactation groups, where each group is fed a different ration, matching their needs. In addition to the milking cows, most farms would have one or two dry cow groups. Where dry cows are in two groups, one will be a far-off dry (from the end of lactation until three weeks before calving) and close-up (three weeks before calving until calving) dry groups. Calves will commonly be grouped as follows: (a). three days to three months of age, (b). three months to nine months of age, (c). nine months to 18 months, and (d). 18 months to calving. There are variations on this grouping, but these would be typical. Each of these groups has different nutrient requirements and would receive different rations.

Poultry

- Feed reduced protein diets. The most economical plan would be to feed a starter ration containing 22% CP since no additional benefits were seen by feeding additional protein (Belair et al. 2001).
- Use crystalline amino acids to allow total dietary crude protein to be reduced while still providing adequate amino acids to meet chickens' needs.
- Consider contribution of dietary intake of sulfur from the water supply.

D.2 Buildings

The largest ammonia emissions are generated from livestock buildings. There are some control measures to reduce ammonia and hydrogen sulfide emissions from livestock buildings. Some of these measures are cost effective, good for the health and welfare of the animals (Ekman 1998), and could be easily applied.

Benefits

Research in North America and Europe has found that using a variety of practices has dramatically reduced ammonia and hydrogen sulfide levels in livestock buildings. The applicability of such techniques will depend on the housing system, ventilation of building, and type of feeding.

What Can the Producer Do?

- Keep deep-bedding packs of straw, wood or other materials in facilities for growing finishing pigs. Carbon/nitrogen ratios of 36:1 or greater permit carbon in the bedding to bind ammonia nitrogen and prevent it from volatilizing. Generally, maintain the top of the bedding pack to provide a dry and comfortable environment for the animal. This should help maintain a high C/N ratio and keep ammonia emissions negligible. Research shows that operating costs for a deep straw system can be higher because of the seasonality of the hogs' feed as well as the increased labor needed to haul bedding as much as twice a week (Land Stewardship Newsletter, Nov 2000).
- Control dunging patterns and maintain pens in dry, hygienic condition to reduce the gaseous evaporation from dirty surfaces. Dunging could be controlled by feeding pigs on a clean floor during the first few days and training them about dunging patterns. *Developing good dunging habits of swine on partially slotted floor* is an informative factsheet developed by British Columbia Ministry of Agriculture and Food. This factsheet contains 16 recommendations that encourage good pig dunging habits.
- Use the new "pull-plug" system that utilizes manure trays under slatted areas and large PVC pipes that are used to transport the liquid manure from the buildings to outside manure storage (Banhazi and Gargill 2000).
- Use a manure board and scraper system in poultry housing to dry manure and lower NH_3 emission. Other systems allow direct dropping of manure into storage area.
- Collect manure located under the slatted floor in about 4 in. of flushing water, so manure falls into liquid and solids are submerged. If the mixture is regularly pumped out and replaced by new flushing liquid (as in pit recharge), the emission reduction will be about 60%. However, using more water increases the volume of manure if fresh water is used for flushing, and this will increase the cost of hauling and applying manure.

- Use partially slotted, sloping floors under slats from which manure is flushed several times a day. This technique can reduce the NH_3 emissions by 30% compared to deep pit systems.
- Scrape manure frequently. This will reduce ammonia losses, primarily because it determines how long and to what extent the manure is exposed to the air. In general, frequent (i.e., daily) removal of manure tends to conserve manure N. If stored immediately, there is less surface area exposed from which ammonia release can occur.
- Remove manure by a manure belt system under the cages twice a week. This practice can reduce ammonia emissions compared to stair-step laying cage system.
- Flush manure from the floor with water. Research has found that flushing will eliminate ammonia emissions from animal housing. Flushing has the disadvantage of increasing manure volume, thereby increasing transportation and application costs.
- Improve the building ventilation system by increasing airflow rates, modifying and controlling air distribution system (Heber et al. 2001). The design and management of ventilation inlets can have a significant effect on the resulting air speeds across the pen floor, especially in mechanically ventilated buildings. Incoming air should travel across the building first (very close to the ceiling in negatively ventilated buildings) and then down to the floor. By that time it reaches the floor level, the speed of the fresh air should be relatively low (Banhazi and Gargill 2000).
- Cool the top 4 in. of slurry to 15°C or lower by recirculating ground water in a closed-loop geothermal system. The initial investment cost was $45.00 CAN per pig space, and the annual cost was $5.60 CAN per pig space (Heber et al. 2001).
- Use biofilters or bioscrubbers to absorb ammonia from polluted air. This is done by microbial oxidation of ammonia into NO_2 and NO_3. Biofiltration and bioscrubbing methods are still under research and development. Bioscrubbing is very expensive.
- Use a soaker system to sprinkle soybean oil inside swine finishing buildings daily. This technique will significantly reduce the indoor concentration and emission of NH_3. The oil sprinkling system tested by Jacobson et al. (2002) in a swine finishing building has a low initial cost (about $300 US per 1000-head barn or room) and an operating cost of roughly $5 US a day for a 1000-head size unit.
- Lower indoor temperature to reduce hydrogen sulfide emissions. Studies found a positive correlation between air temperature inside the building and hydrogen sulfide emission. High temperature under a certain limit may enhance the generation of H_2S in manure pits (Ni et al. 1999). Temperature below 10°C strongly decreases NH_3 emissions from livestock buildings (CIGR 1994).

D.3 Manure Storage

a. Solid manure

Manure storage facilities could be a source of ammonia and hydrogen sulfide emissions. Open manure systems are always subjected to fluctuating environmental factors, which in turn, affect ammonia and hydrogen sulfide emissions.

What Can the Producer Do?

- Maintain solid content of manure at an optimum range. The moisture content of stored manure impacts ammonia release. Highest ammonia emissions occur from stored beef slurry at a low solids content (around 2%). Increasing total solids decreases N losses. At 20% - 30% total solids, ammonia release is minimal.
- Keep feedlots well drained and keep the watering systems in good condition. Proper operation and management of feedlots is necessary for gaseous emission and odour control. For more information on feedlot runoff control see page 34 of Environmental Manual for Feedlot Producers in Alberta.

b. Liquid manure

Covers are the main technique to reduce emissions from liquid storage.

A cover is a permeable or impermeable material that is placed on top of liquid storage units to provide a physical barrier between the liquid manure surface and the air. Placing a permeable cover or biocover on liquid manure storages and bottom loading control NH_3 emissions by:

- Physically limiting the emission of ammonia and other gases from the surface of storage lagoons, and
- Creating a biologically active zone on the top of the covers where the emitted ammonia and other gases will be aerobically decomposed by microorganisms.

Covers consist of floating layers of chopped barley, wheat, flax, brome straw, corn stalks, peat moss, sawdust, wood shavings, rice hulls, Polystyrene® foam, air-filled clay balls like Leca® and Macrolite®, and geotextile. Biocovers can greatly reduce ammonia and hydrogen sulfide from manure lagoon and cost less than synthetic covers. The disadvantages of biocovers are that they need to be replaced frequently as the floating material sinks to the bottom and adds to the sludge build-up.

Benefits

- Reduced ammonia emissions. Plastic inflated covers can reduce odour and ammonia emissions between 80 and 95%.
- Reduced hydrogen sulfide emissions. Straw covers (12 in. thick) can reduce hydrogen sulfide from swine manure tanks by 82 to 94%.

What Can the Producer Do?

- Use deep storages to reduce the surface area. Many operators prefer a 12-foot depth since this reduces the precipitation and freeboard requirements to 17% of the storage volume (OMAF, 1997).
- Cover lagoons with a synthetic cover to limit the release of malodorous gases from the surface of the basin.
- Aerate manure to achieve nitrification and reduce the ammonia concentration. Manure could be aerated naturally or mechanically. Natural aeration is not practical during cold weather. Mechanical aeration is carried out by mechanical aerators that mix air into manure. Mechanical aeration is expensive and inefficient during cold weather.
- Avoid over agitation. Agitate only prior to land application and to allow homogeneity of manure.
- Fill and empty tanks below the liquid surface, and recycle exhaust air from tanker back into manure store whenever practical and safe.

D.4 Manure Additives

Manure additives are chemical or biological substances added to manure to reduce the emission of ammonia and hydrogen sulfide by: directly adsorbing NH_4^+ and NH_3; reducing the manure pH; promoting microbial production of organic acids such as lactic acid, that reduce the manure pH; increasing microbial N immobilization; and inhibiting microbial growth. The effectiveness of an additive depends on which compounds are causing the emission problem. The equilibrium between ammonium-N and ammonia in solutions is dependent upon pH, high pH favors loss of ammonia, and low pH favors retention of ammonium-N.

What Can the Producer Do?

- Acidify manure (pH 3 to 5) with lactic acid or other organic acids to reduce ammonia. Studies have shown that you can create lactic acid fermentation conditions by the addition of lactic acid bacteria. It also helps to maintain the bacterial culture with potato starch or milled wheat. These reduce ammonia by 80%.
- Lower the slurry pH to 4-5 by adding strong acids (e.g. nitric or sulphuric acid). This technique can decrease ammonia emission by 30-95%.
- Add hydrated lime to reduce levels of hydrogen sulfide, but it may increase ammonia emissions.
- Treat manure with hydrogen proxite (or peroxide). The treatment is highly effective in reacting with manure and reducing odorous gases such as ammonia and hydrogen sulfide.
- Use poultry litter amendments (alum). These products can be added to litter, feed or water to chemically or biologically reduce the ammonia volatilization rate from litter. By reducing the ammonia losses from litter, the nitrogen content and value of the litter may be increased.

D.5 Manure Application

The method of manure application is the single most important management factor impacting ammonia release. The rate at which ammonia is produced will be proportional to the contact surface area between the manure and air. Two types of manure injection are currently available. Shallow closed-slot injection is more efficient than open-slot in decreasing ammonia emissions.

Benefits

- Injection of manure into the soil reduces NH_3 losses compared to other surface application methods. The reduction in ammonia emissions by injection could reach up to 80% but it will also result in the increase of nitrous oxide emissions from agricultural soils by up to 100%. However, the exact magnitude is not known at this time.
- Incorporation of manure immediately after spreading could result in reducing ammonia losses substantially. Immediate manure incorporation into soil is cost effective and a practical way to substantially reduce the emission of ammonia and hydrogen sulfide.
- Banding liquid manure on the soil surface beneath the crop canopy using drop hoses or 'sleighfoot' applicators can reduce ammonia emission relative to broadcasting by up to 80%. Generally banding conserves ammonia by reducing exposure of manure to air, but works best under a crop canopy, which both reduces advection and directly absorbs up to 40% of released ammonia.
- The timing of application is an important consideration affecting release of manure N into the atmosphere. Ammonia loss is generally greater during the spring and summer. The rate of ammonia emission will be reduced if manure is spread in winter because ammonia losses are directly affected by wind speed and temperature, which are normally low in winter months. Do not spread manure on frozen or snow-covered ground to avoid runoff that can pollute surface water.
- Manure N emission can be increased by selecting application areas with alkaline soils (pH greater than 7) of low clay and organic matter contents.
- High initial soil moisture further enhances ammonia release. When soil type and conditions allow rapid infiltration of liquid, ammonia emission decreases with decreasing manure dry-matter content.
- Dilution of manure with water not only decreases the ammonium-N concentration but also increases the rate of infiltration into the soil following application, but the dilution of manure by water is sometimes impractical due to transportation costs.

What Can the Producer Do?

- Inject manure downwards into the soil, using a band-spreader or low trajectory splash-plate.
- Incorporate surface-applied manure as soon as possible after application, preferably as it is applied.
- Reduce application rates of surface-applied manure to promote drying and reduce ammonia and hydrogen sulfide release.
- Use an application method that reduces exposure to air (e.g. low-pressure irrigation near surface, drag or trail hoses).
- Avoid spreading manure on wet soil because ammonia emissions are high when manure is spread on wet soils rather on dry soils.

D.6 Summary

By putting these BMPs into practice, ammonia and hydrogen sulfide emission losses from the storage, handling, and use of manure livestock can be controlled. Implementing these BMP strategies can be both economically and environmentally desirable for producers. Producers are advised to seek the most cost effective and easy-to-implement BMPs.