Particulate Matter: Public Concerns and Control Measures

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Documented Human Health Effects of Airborne Emissions from Intensive Livestock Operations

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Abstract

We have compiled over 900 articles and abstracts from refereed journals, regulatory documents and conference proceedings concerned with the health effects of airborne emissions from intensive livestock operations (ILOs), including beef and dairy cattle, swine, sheep and goats. Where general indicators of risk to public health have been associated with emissions from other livestock species, with poultry production or with occupational exposures (e. g., pulpwood processing), those data have also been included. Emissions classes considered in the literature review include particulate matter (PM), ammonia (NH_3), hydrogen sulfide (H_2S), bioaerosols, volatile organic compounds (VOCs) and odor. Public health effects considered in the review include direct respiratory impairment, sensory irritation, synergistic effects of multiple pollutants and psychological effects of nuisance pollution. The depth and breadth of literature on this subject vary substantially among livestock species and appear to be functions of the degree of confinement typical of each. Species generally produced in total confinement (i. e., under roof) have received the greatest attention.

In general, time-averaged *ambient* concentrations of single, high-profile, discrete pollutants (e. g., NH_3, H_2S) do not appear to exceed exposure thresholds for human health. The human health implications of complex mixtures of pollutants, including PM, bioaerosols and odors, are more difficult to establish and are therefore a fertile area for research. Known occupational health effects of all of the air pollutants considered herein represent a reasonable but incomplete basis for future research into the epidemiological significance of ambient exposures. Even though direct causal relationships between ILO emissions and epidemiological responses in the general public are virtually nonexistent in the refereed literature, the larger corpus of published data from clinical and engineering research suggests that selected circumstantial linkages offer a reasonable basis for further inquiry.

Specifically, we found that:

1. The validity and quality of published epidemiological and quasi-epidemiological relationships between (a) ILO odor and (b) psychological responses such as mood and stress need to be evaluated according to olfactometric data (i. e., actual human exposures), distances between sources and receptors and actual weather data;
2. Known associations between agriculturally derived endotoxin and syndromes such as farmer's lung and byssinosis indicate that property-line and downwind concentrations of endotoxin-laden particulate matter from ILOs may have intermittent (and, perhaps, long-term) clinical significance;
3. The persistence of airborne, Gram-negative respiratory pathogens apart from their hosts or sources is a relatively recent finding and may warrant incremental clinical examination, but we found no compelling association between ILOs and increased pathology (i. e., in the general public) traceable to such microorganisms suspended in ambient air downwind of ILOs;
4. Synergistic effects of NH_3 and PM on the respiratory health of animals invite further inquiry in the context of human health;
5. Occupational exposures to the full range of ILO emissions, in general, are often significant in fully confined livestock facilities and, to quite a lesser extent, in open-air facilities; and

6. Where respirable, secondary PM has been linked with public health effects, the contribution of ILOs to regional NH_3 enrichment may be an indirect and partial cause. However, an assessment of ambient concentrations and formation kinetics in relation to (a) atmospheric residence times and (b) credible apportionment of NH_3 sources is needed before epidemiological study of ILO neighbors is justified in the context of respirable, secondary PM.

Motivation and General Approach

The idea that air pollution arising from confined livestock production may impair the health and quality of life of neighbors and nearby communities has potentially explosive implications for the economic and social forces that drive the growth and incremental dislocation of the ILO industry. As is the case with any industry whose expansion poses unknown environmental risks, stakeholder groups who elect to play a role in shaping environmental policy with respect to that industry are numerous and diverse. That diversity, moreover, is expressed in several dimensions (social, political, economic and scientific) as stakeholder groups begin with unique presuppositions in each of those dimensions. Groups whose presuppositions contrast most starkly find it difficult to establish a solid foundation for cooperation in the development of mutually beneficial public policy. To the extent that such cooperation is vital to long-term sustainability of both industry and community (we assume that it is), credible science can play a modest but important role in reducing or circumventing those fundamental barriers to cooperation.

We recognize at the outset, therefore, that public health authorities and livestock producer associations in Canada operate with vastly different mandates (i. e., from their respective constituencies) and with vastly different scientific presuppositions that express those mandates. In general, the public health official is concerned with discovering and exposing possible risks to public health without regard to the economic implications of his findings. If he is to err, he will elect to err on the side of exposing risks that may not be real so that the public is, in effect, overprotected. In this frame of reference, causation may appear to take a back seat to association, at least when considering whether to go public with preliminary findings. The public health agency's mandate requires it. (Clearly, subsequent decisions about allocating scarce public resources demand a greater degree of confidence in causal mechanisms.)

Typically, regulatory agencies are required by statute to establish protective thresholds in response to public and political demand, even when little data exist to support such thresholds. This pressure to set standards in the face of little supporting scientific data and the inherent "uncertainty" typically results in extremely conservative standards. The regulators rely on the affected industries and further research to provide the dose/response data needed to reduce the overall uncertainty associated with the standard(s). As such, it is the industries' best interest to take an active part in the development of reliable dose/response relationships and then to develop risk management plans to address those issues and to protect the public and industry workers. *In virtually all cases, the unknown is perceived to pose a much greater risk than the known.* So it is desirable to bound the true risk and communicate that risk to the public, regulators and workers.

The livestock producer association, and the agricultural research community more generally, tend to focus on research whose purpose is to identify inefficiencies, develop technologies and clarify causality in search of competitive advantage in the marketplace. Resource allocation is among the first questions asked by agricultural enterprises, who cannot afford to waste resources developing knowledge that has little potential for immediate return or that has great potential for accelerating losses. The agricultural community, composed of individuals whose livelihood depends on sustainable profit growth, demands such a conservative outlook. (Clearly, agricul-tural interests actively recognize that the social and ethical implications of their activities and products are also critical to the sustainability of their enterprises and communities.)

In the immediate context of health effects from ILO emissions, the fundamental conflict between these competing presuppositions or frames of reference is strikingly clear. The public health official must not narrow his focus to the point that he misses an unanticipated threat to public health. The agricultural community must not cast its research net so widely that it fritters away its profit margin on fruitless endeavors or inquiries in which the mere statement of a hypothesis would be socially explosive (and, hence, economically disastrous to the industry).

Resolving the conflict between the competing views[1] has both technical and social dimensions, and those dimensions are somewhat interrelated. Still, although science cannot solve this central conflict, it can and must inform both the technical and social dimensions of the solution from the outset. Further, it must embrace all of the competing presuppositions in an objective and unbiased way if its influence is to be sustained.

This literature review is not intended to be the final word in the design of a cooperative research agenda. Our goal in this literature review has been simply to present the modern state of knowledge concerning the health effects of airborne emissions from ILOs in a comprehensive (certainly not *exhaustive*) and objective way that:

1. Informs the principal stakeholders;
2. Embraces their presuppositions;
3. Identifies key scientific gaps; and
4. Provides a basis for further discussion and cooperative action.

In recognition of the ILO industry's need for scientific certainty, we have emphasized conclusive, refereed literature when evaluating etiology, emissions characterization and dose/response relationships. Where hard and comprehensive epidemiological evidence is lacking but components of the exposure/dose/response continuum are individually compelling, however, we have drawn more liberally from monitoring surveys, agency reports and conference proceedings in an effort to outline credible causal pathways deserving more attention.

Because of the huge compendium of reference materials that have been assembled (nearly 1,000), we have made no attempt (a) to summarize every single reference within the body of this review document or (b) to pass judgment on the details of experimental or analytical methods used in their preparation. As to (a), we have submitted this written review to the project sponsor along with a complete bibliographical database in Microsoft Access 97 format. Readers interested in more detail about particular subjects may find the database useful as a road map for further inquiry. In this written document, we have attempted to capture the most compelling, recent or trenchant insights that contribute to a broad understanding of the technical issues that face the stakeholders. Regarding the technical critique, (b), we have assumed that the traditional peer review process has screened out those studies or aspects of studies that were technically deficient. From time to time, we have identified remaining, frequently noticed deficiencies that have major implications for the interpretation of findings in a risk assessment, communications or policy framework. Non-refereed articles receiving attention in the text have been clearly labeled as such.

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[1] Several participants at a recent ILO workshop sponsored by the U. S. Center for Disease Control and Prevention (CDC, 1998) captured this conflict by suggesting that, "the public should not have to prove adverse effect; instead, industry should make sure that [ILO] exposures do not pose a public health risk before any more [ILOs] are built." Scientists taking the opposing view might counter that proving the absence of risk is simply not possible and that the insurmountable nature of that burden of proof would effectively halt industry growth.

Introduction

Intensive livestock operations (ILOs), also known as animal feeding operations (AFOs) or confined animal feeding operations (CAFOs), are experiencing phenomenal growth throughout North America. The industry's growth has been accompanied by trends in suburban sprawl, decreases in population with rural backgrounds, global economic forces that reward economies of scale and a small but steady stream of environmental disasters associated with confined animal production. Together, these trends have engendered and intensified conflict at the rural-urban interface (e. g., dairy farms on the East and West Coasts) and in rural areas where unfamiliar animal species have recently been introduced (e. g., hog farms in the West's "cattle country"). Among the major environmental flash points are concerns about the effect of air pollution from ILOs on the health and well-being of neighbors and employees. In fact, a 1998 ILO workshop (CDC, 1998) elected to adopt the definition of health proposed by the World Health Organization (WHO): "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity." Although such a definition leaves open the question of what constitutes "well-being," it nevertheless underscores that social, cultural and psychological pathologies are as significant to the modern, Western public as physiological insult.

The alleged effects of ILO emissions on health range from acute toxicity of hydrogen sulfide to dust allergies to psychological stress from nuisance odors. Gaseous emissions from ILOs, like those from municipal wastewater treatment plants (MWTPs), are complex, variable mixtures of dozens to hundreds of individual gases and vapors, each having a unique odor potential. Particulate matter (PM) emissions, often known colloquially but imprecisely as dust, are also complex and variable, composed of a wide range of materials such as soil particles, bioaerosols (e. g., fungi, spores, bacteria, viruses), processed feed, dander and hair. In addition, PM emissions from ILOs may themselves be odorants or odor carriers (Pain, 1994).

Emission sources within ILOs are many and varied. Because most potent odorants are generated in the absence of oxygen, liquid manure handling systems such as deep pits, lagoons and "slurrystores," as well as confinement structures (i. e., ventilation systems) and runoff holding ponds, are the predominant odor sources on a day-to-day basis. Likewise, silage pits, high-moisture grain storages and other feed handling systems generate odors and off-gases continuously. Intermittent odor releases from open-lot ILOs follow precipitation events as wet manure on the corral surfaces becomes anaerobic. PM emissions arise from hoof action on dried manure, manure handling and composting systems, vehicle traffic on unpaved roads and grain and feed handling. Even when little odor is apparent, all of these sources emit a wide range of gases that are known to cause human health effects at unique threshold concentrations. (Some authors, such as Lipfert (1997), have questioned the validity of the "threshold concentration" concept in the context of human health effects from air pollution.)

In this review, we have compiled more than 900 citations that address different aspects of the health implications of emissions known to be associated with ILOs. Although the bibliography is by no means exhaustive, it represents a reasonably comprehensive database of the current scientific knowledge about the subject. We begin with an overview of the different classes of emissions, outline the known human health thresholds for the major emissions classes and identify the key sources of those emissions. Next, we document the ranges of ambient concentrations and occupational exposures that have been measured by scientists for each emissions class. Finally, we compare the documented, measured concentrations with health effects thresholds to assess the general risk posed to human health by each emissions class, identifying the major gaps in knowledge to be filled by research in the near term.

Classes of Emissions

Major Gases

We use the term “major gases” to refer principally to gases that are released in large quantities from livestock facilities and manure and wastewater handling and storage, as well as those having a high profile with the general public. The major gases considered in this review are ammonia (NH_3) and hydrogen sulfide (H_2S), with cursory attention paid to carbon monoxide (CO) because of its widely known lethality as an automotive combustion product.

Trace Gases

Trace gases, as we are using the term, refer to *classes* of individual compounds routinely found in the gas phase that are released by livestock facilities in minute quantities compared to NH_3, H_2S and CO. *Individual* compounds within these chemical classes (e. g., propionic acid) may be released at rates approaching those of the major gases.

Particulate Matter

Particulate matter (PM, often referred to erroneously as *dust*) is a complex mixture of suspended particles of variable origin, composition, size, shape and density. In the context of air pollution and human or veterinary health, the most widely-accepted basis for comparing different types of PM is the aerodynamic equivalent diameter (AED), which is the diameter of a spherical water droplet whose aerodynamic performance (usually, settling velocity in air) most closely approximates that of the particle in question. Thus, a particle of road dust having the same settling velocity as a 10-micron spherical droplet of water would be considered part of the PM_{10} fraction. In most accepted literature on the subject, the PM_{10} designation refers to particles whose AED is *less than or equal to* 10 microns, so that all $PM_{2.5}$ (for example) is contained within the PM_{10} fraction, but the converse is not true.

Bioaerosols

Bioaerosols include microorganisms (living, dormant or non-viable) such as bacteria, viruses, fungi and actinomycetes, as well as the biochemical compounds (e. g., endotoxin, mycotoxin, aflatoxin) that are uniquely associated with the microorganisms. Bioaerosols are ubiquitous around ILOs, deriving from the animals themselves, their feeds, their excreta and their human stewards.

Odors

Although we distinguish (Schiffman, 1998) between *odorants* (the gas-phase chemicals *per se*) and *odors* (i. e., the unique and subjective perception of those odorants by the human olfactory system), it is common to hear the two terms used interchangeably. The semantic difference between the two terms is significant primarily in the context of measuring and regulating them. Odorants, including both the major and trace gases described above, may be objectively and precisely quantified using standard laboratory techniques (e. g., gas chromatography/mass spectrometry) that apply to non-odiferous compounds as well. However, quantifying odors is considerably more complex, subjective and imprecise. Characterizing odor involves at least four dimensions, sometimes known as the FIDO factors:

1. *Frequency*: How often does the odor occur?
2. *Intensity*: How much odor-free dilution air would be required to render the odor undetectable to 50% of human panelists? Alternatively, what mass concentration in air of a reference odorant (e. g., *n*-butanol) would appear as strong or intense as the odor in question?
3. *Duration*: How long does the odor event last?
4. *Offensiveness*: Where does the odor rank in the pleasant/ unpleasant continuum?

Other dimensions such as *persistence* (the slope of the curve relating intensity to concentration) and *hedonic tone* (what the odor smells *like,* as in “medicinal” or “fishy”) are also important considerations. Intensity and concentration are quantitative measures; offensiveness and hedonic tone are qualitative or semi-quantitative measures. Intensity, usually expressed in units of dilutions to threshold (DT), is the odor measurement most frequently associated with regulation or nuisance determination.

Shusterman (1992) has described human responses to odor and odorants in the context of two primary sensory systems, the olfactory and trigeminal systems. The dominant system that operates in response to a given compound or mixture of compounds depends on the concentration(s). As concentrations increase, human responses proceed through benchmarks of (a) detection, (b) identification or recognition, (c) annoyance and (d) irritation as shown in Figure 1.

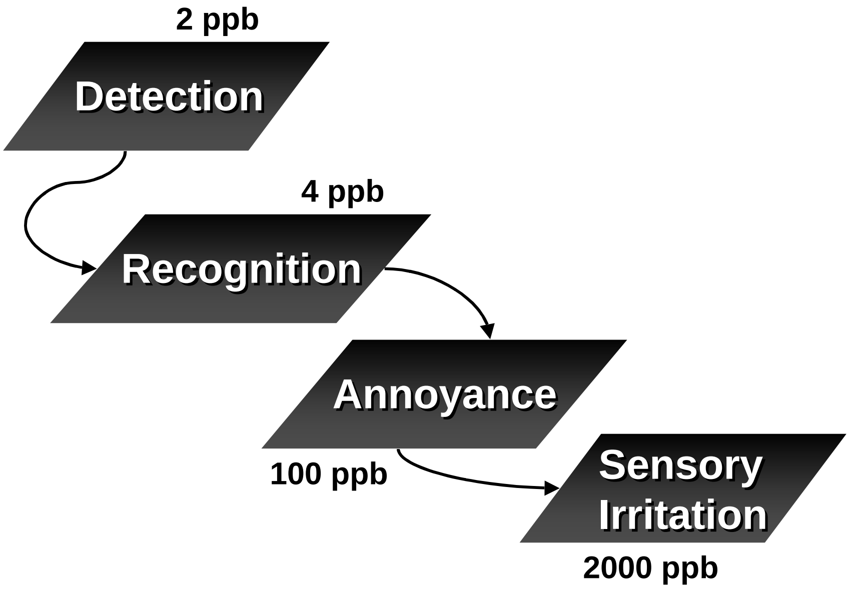

Figure 1. Human responses to odorants are a function of the concentration to which one is exposed. Values listed are for hydrogen sulfide (H_2S).

The detection threshold of an odorant is its concentration in air at which 50% of human panelists are able to detect the presence of the odor correctly without recognizing the odorant specifically. In general, each human panelist is presented with two or more streams of air, one of which has the odorant at a known concentration. The other stream(s) is so-called “odor-free” air, which usually has been deodorized by drying it and passing it through a filter of activated charcoal or other adsorbent media. The panelist must blindly choose which of the streams of air contains the odorant. The 50% (median) response criterion reduces the influence of hypersensitive and hyposensitive panelists (panelists whose ability to detect the presence of odor is consistently well outside the normal range) in determining detection thresholds.

With so many different classes of compounds contributing to livestock odor, humans’ physiological responses to odorants are many and varied. Even different compounds within a class of odorants or different isomers of the same compound may give rise to different physiological (either health or olfactory system) responses. The following section explores the major odorant classes and their most extensively documented dose-response characteristics. For comparison, typical occupational exposures and ambient concentrations are presented where published data are available.

Human Health Thresholds by Emissions Class

Major Gases

Ammonia (NH_3)

NH_3 is an ubiquitous, odorous air constituent that originates from a wide variety of sources. Its hedonic tone is distinct and pungent. Environmental concentrations of NH_3 occasionally rise to levels that induce irritation of the eyes and upper respiratory tract. In the United States, it is not regulated as one of the so-called *criteria pollutants* (lead, ozone, particulate matter, carbon monoxide, sulfur dioxide, nitrogen oxide) under the Federal Clean Air Act, so no ambient standards have been set in the United States for NH_3. (It is more tightly regulated in Europe.) Among the recommended threshold levels and occupational standards for NH_3 are:

- Occupational (8-hr average) 25-50 ppm (TOMES, 2000).
- Recommended ambient lifetime exposure 0.1 mg m^{-3} (IRIS, 2000).
- Donham et al. (1989) stated that “recommended healthful concentrations for farmers may be significantly lower than TLVs for industrial workers.” They recommended an 8-hour exposure limit of 7 ppm for NH_3, 72% lower than the lowest industrial occupational limits. More recently, Donham and Cumro (1999) have recommended an 8-hr standard of 12 ppm for poultry workers.
- Inhaled NH_3 is lethal at concentrations in the neighborhood of 5000 ppm (ATSDR, 2000)

Hydrogen Sulfide (H_2S)

H_2S is a potentially lethal gas to man and to livestock. Many cases of premature death from H_2S exposure have been associated with poor ventilation during agitation and pumping of manure slurry from underground pits. Miner (1973) reported that H_2S is toxic to humans at 500 ppm, causes dizziness and irritates the eyes at between .002 and .01 percent and causes instant death at 0.1 percent. H_2S is among the most well known occupational hazards for individuals working in the confined livestock industry. Denser than air, H_2S accumulates near (or below, in the case of manure pits) the floor in enclosed livestock houses. Workers may encounter lethal concentrations of H_2S when manure pits are agitated and pumped out. Baker et al. (1986) report 600 ppm as an H_2S threshold where rapid death is likely. With notable exceptions (associated mainly with agitation and pumping of stored, liquid manure), livestock production does not appear to elevate environmental H_2S concentrations to levels that would routinely affect occupational or public health in isolation from other air pollutants. Among the recommended threshold levels and occupational standards for H_2S are:

- Occupational (8-hr average) 10 ppm or 15 mg m^{-3} (TOMES, 2000)
- Recommended ambient lifetime (RfC) exposure 1.0 μg m^{-3} (IRIS, 2000)

Carbon Monoxide (CO)

CO, a well known air pollutant resulting from incomplete combustion or oxidation of organic materials, has an affinity for hemoglobin and displaces oxygen in the blood (Lipfert, 1994). Acute exposures at concentrations of 1000 ppm can be fatal. Long-term exposures at lower concentrations are known to accelerate artherosclerosis and induce spasms in coronary blood vessels. Among the recommended threshold levels and occupational standards for CO are:

- Occupational (8-hr average) 29-50 ppm or 20-55 mg m^{-3} (TOMES, 2000).
- Recommended ambient lifetime (RfC) exposure. NA (IRIS, 2000).

Trace Gases

There are more than 170 trace gases (odorants) emitted by livestock and poultry facilities, many of which are listed by various regulatory agencies as hazardous substances or hazardous air pollutants. Threshold Limit Values (TLVs) or other relevant health-based standards for a cross-section of these compounds are listed in Table 1 in the Appendix.

Particulate Matter

Discrete fractions of particulate matter are frequently designated as PM_x, where x is an aerodynamic equivalent particle diameter (AED) as described earlier, and PM_x then refers to that fraction of suspended PM having an AED less than or equal to x. As the epidemiological evidence of respiratory insult has grown more conclusive, regulatory agencies worldwide have elected to regulate smaller and smaller particles. In the 1970s, total suspended particulate (TSP; see Lipfert, 1994), which is composed of particles up to 50 μ AED, was the fraction of interest. In the late 1980s, ambient PM_{10} standards (so-called “inhalable” particles) replaced TSP standards, and in the late 1990s, ambient $PM_{2.5}$ standards (so-called “respirable” particles) took their place alongside the PM_{10} standards. Many countries have taken their cues on ambient PM standards from the United States, where 24-hour ambient standards for PM_{10} and $PM_{2.5}$ are 150 and 65 $\mu g\ m^{-3}$, respectively. The respective annual standards for the two fractions are 50 and 15 $\mu g\ m^{-3}$. Donham and Cumro (1999) proposed threshold occupational standards (8-hr nominal) for poultry workers of:
2,500 $\mu g\ m^{-3}$ TSP and 250 $\mu g\ m^{-3}$ respirable PM.

Bioaerosols

We found no broad-based exposure thresholds for airborne microbes, but the literature is replete with recommended standards for bacterially derived endotoxin. Because endotoxin is associated with microbial particulate matter, recommended exposure standards are frequently divided into total and respirable endotoxin. However, after examining the concentrations of endotoxin associated with different particle sizes, Donham and Cumro (1999) concluded that endotoxin was present at similar concentrations across all particle size ranges. They recommended a work-shift standard for poultry workers of 600 endotoxin units (EU) m^{-3}. Takai et al. (1999) reported that the Dutch and German occupational mass exposure limits for endotoxin are 10 ng m^{-3}.

Odors

Feedyard odor results from the interaction of a complex mixture of odorants with an array of sensory receptors in the human body. Nearly 200 individual compounds emitted by livestock or livestock manure have been associated with measurable odor responses in humans. The profile of compounds associated with livestock odor is likely to be species-specific because of differences in physiology and diet composition, but these compounds can be broadly classified in a manner that may be generally applied to all livestock species:

- volatile organic acids;
- trace sulfurous compounds;
- trace nitrogenous compounds;
- phenolic compounds; and
- alcohols, ketones and aldehydes

A key distinction exists between the health effects of (a) exposure to feedyard odors and (b) exposure to the odorants themselves, compounds *associated with* ILO odor. In the former case, health effects are principally psychological and relate to the overall sensation of odor, which may depend strongly on conditioning, experience and cultural factors. In the latter case, however, human health effects are more clearly physiological and may frequently be linked to identifiable modes of action (e. g., asphyxiation, bronchoconstriction). Significant psychological odor responses often occur at concentrations well below physiologically significant levels. Of course, physiological and psychological effects are not entirely independent and may be mutually reinforcing. In both cases, the combined effects of multiple odorants may be additive, synergistic, potentiating or antagonistic.

Ammonia (NH_3) and Hydrogen Sulfide (H_2S) as Odorants

Although research surveys of gaseous emissions from cattle feedyards are in their infancy, ammonia (NH_3) and hydrogen sulfide (H_2S) are likely to dominate the emissions profile in terms of total mass emitted. The hedonic tones (what the odor smells like) of NH_3 ("glass cleaner") and H_2S ("rotten eggs") are distinct and widely recognizable. Although these compounds are undeniably odorous, concentrations of NH_3 and H_2S in ambient air are unreliable predictors of the intensity of livestock odor as perceived by human panelists (McGinn, 2000; Zhu et al., 1999).

Ammonia (NH_3). Although European researchers have studied NH_3 releases from livestock facilities for some time, North American attention has turned to NH_3 releases only recently as it pertains to (a) odor and (b) the formation of secondary particulate matter by combining with atmospheric nitrate and sulfate ions. As an odorant, the potency of NH_3 is overrated by the public, perhaps because it is present almost everywhere and because of its relatively high concentrations in air as compared to other odorants associated with livestock production. At concentrations up to 20 ppm, NH_3 is an eye irritant (Doss et al., 1993). At concentrations between 40 and 200 ppm, exposure symptoms include headache, nausea, appetite suppression and upper respiratory irritation (Baker et al., 1986).
The odor detection threshold of NH_3 is approximately 5 ppm, and its one-hour exposure guideline in Alberta, which is clearly not a health-based threshold, is 2 ppm.

Hydrogen Sulfide (H2S). H_2S is among the most well known occupational hazards for individuals working in the confined livestock industry. Denser than air, H_2S accumulates near (or below, in the case of manure pits) the floor in enclosed livestock houses. Workers may encounter lethal concentrations of H_2S when manure pits are agitated and pumped out. It is an irritant at concentrations between 2 and 20 ppm (well above its detection threshold of 2 ppb) and induces nausea between 50 and 100 ppm. At concentrations above 200 ppm, H_2S may cause dizziness, susceptibility to pneumonia and fluid in the lungs. Extreme concentrations (>500 ppm) are potentially lethal within seconds (Doss et al., 1993). At those concentrations, H_2S may paralyze the nerve cells in the nose so that the person is unable to smell the gas and escape danger. Baker et al. (1986) report 600 ppm as an H_2S threshold where rapid death is likely.

Trace Gases as Odorants

Other than H_2S and NH_3, the other gases and vapors typically associated with odor from manure decomposition are trace gases; that is, when detected in livestock odor, they occur in quantities too low to be considered serious physiological threats to human health. At high concentrations (i. e., far beyond the concentrations detected downwind of livestock facilities), many of these compounds are considered extremely hazardous substances for selected regulatory purposes and emergency planning (e. g., spills; see Rogers, 1994). These compounds, as well as H_2S and NH_3, are not unique to livestock agriculture and are emitted in significantly greater quantities from heavy and light industry as compared to ILOs. Even so, they are associated with livestock odor because they tend to have low odor thresholds so that even when their concentration in air is minute, they may affect the sensation of odor and thereby contribute (a) indirectly to physiological health effects or (b) directly to psychological effects. The classes of compounds that tend to be trace gases are often characterized by distinct hedonic tones, although individual compounds may differ in hedonic tone from that of the class as a whole.

Volatile Organic Acids – "Sour"

Volatile organic acids (VOAs), including volatile fatty acids (VFAs), occur in trace amounts but appear to serve as reliable indicators of odor intensity (Zhu et al., 1999). Remarkably, even compounds in this class that are as seemingly harmless as acetic acid (vinegar) are considered hazardous substances in the context of emergency planning regulations (Rogers, 1994). High-strength (20%) acetic acid is commonly used for organic weed control in temperate and subtropical climates.

Phenolic Compounds – "Medicinal"

As measured by their odor thresholds, phenol, p-cresol and their isomers and relatives are among the strongest odorants associated with livestock manure. Like many of the trace odorants, phenols can be extremely hazardous at high concentrations but are detectable as an odorant many orders of magnitude below their hazardous thresholds.

Alcohols, Ketones and Aldehydes – "Sweet" or "Pungent"

This broad class of compounds represents many common by-products of industrial fermentation. Ethanol, for example, is a sweet-smelling alcohol produced by bakeries, breweries and distilleries. N-butanol, another sweet-smelling alcohol, is a standard reference odorant used in olfactometry. These gases are upper respiratory irritants and/or ocular irritants at high concentrations.

Trace Sulfurous Compounds – "Rotten"

Trace sulfurous compounds include assorted mercaptans, sulfides and other by-products of protein metabolism. Butyl mercaptan, for example, is the compound primarily responsible for skunk odor.

Trace Nitrogenous Compounds – "Fishy or Pungent"

These compounds, which include the amines and methylamines, are among the most prominent odorants associated with ILOs. Like the trace sulfur compounds, they are by-products of protein metabolism, and many are considered extremely hazardous (Rogers, 1994) at concentrations far higher than those routinely encountered near ILOs.

Documented Ambient and Occupational Exposures

Major Gases

Ammonia and hydrogen sulfide have been measured extensively in occupational ILO settings but far less frequently in ambient settings downwind of ILOs. Carbon monoxide has not attracted a tremendous amount of monitoring interest in the ILO context. Below are several snapshots of recent occupational and ambient measurements of the major gases.

Ammonia (NH_3)

- Koerkamp et al. (1998) measured instantaneous (i. e., not time-weighted averages) NH_3 concentrations by chemiluminescence in northern Europe livestock housing. Average concentrations in cattle housing were less than 8 ppm. The maximum concentration in dairy housing 22.7 ppm; in beef cattle housing 29.3 ppm; in calf housing 13.7 ppm. Average concentrations in swine housing ranged from 5-18 ppm. The maximum concentration in sow buildings was 43.7 ppm; in finishing barns 59.8 ppm. Average concentrations in poultry buildings ranged from 5-30 ppm. The maximum concentration in layer sheds was 72.9 ppm; in broiler sheds 56.3 ppm. They observed wide variations among countries and seasons, as well as between cattle and other species. In general, cattle barns were naturally ventilated, whereas swine and poultry barns were mechanically ventilated in response to the outside temperature.

- In 1998-99, Alberta Environment measured one-hour NH_3 concentrations downwind of ILOs ranging from 0.011 ppm to 1.364 ppm (Alberta Environment, 2000). Average one-hour concentrations downwind of the eighteen ILO locations ranged from 0.009 ppm to 1.213 ppm.

- Donham et al. (1989) studied the respiratory health of 57 workers on 30 swine farms in southern Sweden and 55 matched controls. NH_3 concentrations measured in swine houses over 3-4 hours using Drager tubes averaged 16 ppm.

- Donham and Popendorf (1985) measured concentrations of selected gases in air in confinement structures on 21 randomly selected swine producing farms in Iowa. Concentrations of NH_3 tended to decrease as growth stage advanced, with concentrations in farrowing houses averaging 42.2 ppm and 20.3 ppm in finishing buildings. The mean NH_3 concentration was 34 ppm. NH_3 concentrations exceeded the Threshold Limit Value (TLV) more frequently than other gases; however, it was common to find buildings with more than one gas at concentrations exceeding its TLV.

- Keener et al. (2000) measured 1-hr NH_3 concentrations in the manure treatment and pig breathing zones of high-rise and deep-pit swine buildings using colorimetric stain tubes. Concentrations ranged from 8-20 ppm in the pig breathing zone and from 10-42 ppm in the manure treatment zone.
- Mean daily concentrations of NH_3 measured by Ni et al. (1998) in various locations within a mechanically ventilated grow-finish swine building were consistently less than 6 ppm.
- Miner (1973) documented the deleterious effects of elevated (100-300 ppmv) NH_3 concentrations on the health and performance of swine, broilers and layer hens. Decreases in feed consumption, egg production and liveweight were common. Reversible health effects included eye disorders, short breathing, oral and nasal frothing and secretions, sneezing and convulsions. He also cited other research wherein NH_3 concentrations in swine buildings ranged from 7 ppm at full ventilation rates to 19 ppm when ventilation ceased for 6 hours.

Hydrogen Sulfide (H_2S)

- H_2S concentrations measured in swine confinement buildings by Donham and Popendorf (1985) averaged 1.4 ppm.
- Miner (1973) cited research wherein H_2S concentrations in hog barns ranged from 0.09 ppm under full ventilation to 0.28 ppm after ventilation had ceased for 6 hours.
- As an example of typical occupational exposures in mechanically ventilated, deep-pit swine barns, Ni et al. (1998) measured daily average H_2S concentrations between 38 and 536 parts per billion (equivalent to 0.04 to 0.5 ppm), with 12-minute averages up to 1.6 ppm, one-sixth of Alberta's 8-hour Occupational Exposure Limit (OEL) of 10 ppm (Alberta Environment, 2000).
- One-hour averaged H_2S concentrations downwind of Alberta feedyards and swine facilities (Alberta Environment, 2000) ranged from below the minimum detection limit of 0.6 ppb to 54 ppb; the mean one-hour measurement was 4 ppb. Alberta's one-hour guideline for H_2S, 10 ppb, is based on odor perception, not human health. Remarkably, among the eighteen ILOs in the Lethbridge area where downwind H_2S was measured during 1998-99 (Alberta Environment, 2000), maximum one-hour concentrations exceeding the 10 ppb odor-based guideline were observed only at two locations (26 ppb and 54 ppb). In both cases, these one-hour spikes were 0.5% or less of the 8-hour OEL.

Carbon Monoxide (CO)

Occupational CO concentrations measured in swine confinement buildings by Donham and Popendorf (1985) averaged 9.1 ppm.

Summary

With notable exceptions (associated mainly with agitation and pumping of stored, liquid manure), livestock production does not appear to elevate environmental H_2S, NH_3 or CO concentrations to levels that would compromise occupational or public health in the strict physiological sense as individual compounds. The synergistic or antagonistic effects on human health that these two compounds may have with trace gases or particulate matter are, for the most part, poorly understood. As odorants, NH_3 and H_2S may contribute to psychological malaise that eventually manifests itself in any of a variety of physiological pathologies, but such linkages are difficult to define in any quantitative sense at present.

Trace Gases

- In a literature review concerning gases and odors from confined livestock production, O'Neill and Phillips (1992) compiled reported concentrations of several classes of trace gases, including carboxylic acids, phenols, pyrazines, carbonyls, indoles and sulfides. They cited evidence that some of the trace gases known to be potent odorants (e. g., p-cresol, indole) were associated with dusts from poultry and swine facilities. Reported concentrations (locations and averaging time unknown) of the carboxylic acids and phenols ranged from 0.001 to 617 $\mu g\ m^{-3}$, with the C2-C4 acids occurring at the higher end of the range. The concentrations were measured at various locations within housing units and at the ventilation exhausts. Interestingly, O'Neill and Phillips noted that sulfurous compounds were "rarely detected…in air samples collected outside livestock buildings," which led them to postulate that atmospheric oxidation of sulfur compounds is partially responsible for the extinction of odors with distance (i. e., as opposed to a pure dilution/dispersion effect).

- Ames and Stratton (1991) reported an epidemiological study of individuals exposed to elevated, ambient levels of n-propyl mercaptan in an agricultural setting. This sulfur-containing compound, a potent, onion-like odorant, is a degradation product of ethoprop, a common nematicide applied to potato fields. The California Department of Health Services conducted the study because community residents sought medical attention for odor-related illness. Elevated health effects such as headache, diarrhea, runny nose, sore throat, fever, hay fever and asthma attacks. The authors recommended that human exposures to n-propyl mercaptan be "minimized to the extent practicable," although no exposure data were presented to justify a specific exposure threshold.
- Hutcheson et al. (1982) measured amine compounds at the breathing zone of cattle feedyards, determining that methylamine and trimethylamine (0.06-17 μg N m^{-3}) were present in every sample and that dimethylamine and other trace amines were sporadically detected at much lower levels.

Particulate Matter

<u>Occupational</u>

- In a study of respiratory health in grain handlers, doPico et al. (1986) concluded that occupational grain dust exposure "can induce acute symptomatic and/or physiological inflammatory reactions…and systemic febrile reactions" but that "immediate hypersensitivity to grain dust constituents does not play a major role in the pathogenesis of work-related symptomatic lung disease" in those workers. The effects of grain dust and smoking were additive. They documented long-term increases in certain allergy mediators (IgG and IgA) that appeared to be associated with abnormal airway flow in some workers.
- Clark (1986) studied workers at municipal sludge composting operations and non-exposed controls in the Washington, D. C.-Philadelphia area. He found a consistent increase in EENT infections, self-reported symptoms, white blood cell counts, hemolytic components, compost-derived endotoxin antibody and fungal counts (from oropharyngeal swabs) in the compost workers over those in the control groups. Measured concentrations of endotoxin (~10^{-2} μg m^{-3}) were at least one order of magnitude below the limit of 10^{-1} μg m^{-3} suggested by Rylander et al. (1982) in Canada.
- Keener et al. (2000) measured dust concentrations inside and at the ventilation exhaust of high-rise (HR) and deep-pit (DP) swine barns. Indoor concentrations ranged from a low of 10 μg m^{-3} at the ventilation inlet to 5-6 μg m^{-3} in the middle of the barn and at the exhaust.
- de Haller (1986) associated the prevalence of chronic bronchitis in dairy farmers in mountain valleys of Switzerland with long-term exposure to moldy hay. He cited evidence from Nicolet et al. (1972) that linked decreases of serum precipitins (i. e., against farmer's lung antigens) in beef cattle to the installation of hay-drying equipment in the livestock barns.
- Lecours et al. (1986) performed bronchoalveolar lavage on farm workers who succumbed to acute pulmonary mycotoxicosis (APM; organic dust toxic syndrome) after a short-term exposure to moldy silage and grain during silo unloading. Their case studies, which included spirometry, white blood cell counts and cultures of lavage fluid, led them to a review of APM literature from which they concluded that the incidence of APM in farm workers "is grossly underestimated."
- Pickrell et al. (1993) measured dust and endotoxin concentrations in a swine confinement building and concluded that endotoxin concentrations were highly correlated with particle size, with smaller, manure-derived particles having relatively more endotoxin than the larger, feed-derived particles.
- Collins and Algers (1986) reviewed the literature on the health effects of dust on farm animals, concluding that particulate matter contributed to pulmonary disease both directly (i. e., as a function of

lesions created by the particles themselves) and indirectly (i. e., in response to pathogenic organisms attached to the dust particles).

- Takai et al. (1999) measured PM and endotoxin concentrations in livestock buildings in northern Europe. Mean concentrations associated with cattle were 400 and 100 μg m^{-3} inhalable and respirable dust, respectively; 14 and 1 ng m^{-3} inhalable and respirable endotoxin, respectively. PM concentrations in swine and poultry houses were 3-10 times higher than in the cattle houses, and endotoxin concentrations in swine and poultry facilities were 5-23 times higher than in cattle houses.

Ambient

- 24-hr net (downwind-upwind) TSP concentrations downwind from cattle feedyards in Texas (Sweeten et al., 1998) ranged from 313-862 μg m^{-3}.
- An epidemiological study of PM effects on Italian farm workers and control populations using multiple regression analysis (Saia et al., 1984) suggested an increased incidence of chronic bronchitis and farmer's lung in the farm population; no difference in bronchial asthma between the two sample groups; and lower forced expiratory volume (FEV_1) in the farm population. No exposure data were presented.

Bioaerosols

Bioaerosols have been implicated in a variety of respiratory syndromes, from short-term allergy to intensified asthma and other irreversible diseases, in occupational settings. The main culprits for these syndromes in agricultural workers appear to be molds, fungi and endotoxin; bacteria may also be important, but the evidence is less clear.

Farmer's Lung

A number of microbes associated with hay and grain handling contribute to hypersensitivity pneumonitis, often known as "farmer's lung" or "grain handler's lung," respectively. Syndromes similar to farmer's lung have been identified with exposure to moldy hay at least since the early 1930s (Campbell, 1932). Gudmundsson and Wilson (1999) identify the principal antigens associated with those conditions as *Saccharopolyspora rectivirgula* and *Thermoactinomyces vulgaris*. Related conditions associated with farmers and workers handling bagasse and malted barley also implicate *T. sacchari* and *Aspergillus clavatus*, respectively. All of those commodities are routinely fed to livestock in one form or another. In all of those cases, the source of exposure is moldy or rotten feedstuffs, suggesting that keeping commodities dry while in storage could reduce worker and farmer exposure to these and related antigens.

Endotoxin

Organic toxic dust syndrome (OTDS) is a complex of physiological responses associated with exposure to endotoxin, a biological chemical latent in the cell walls of certain microbes. Endotoxin is quite potent; the National Institute for Occupational Safety and Health (NIOSH) has listed a threshold level of 10 nanograms per cubic meter (ng m^{-3}) for susceptible textile workers (Hughs et al., 1998). Recommended exposure thresholds for previously unexposed individuals range from 80 ng m^{-3} for smokers to 170 ng m^{-3} for students.

Aspergillus spp.

- Occupational exposures to *Aspergillus glacus* and *A. versicolor* in doPico et al. (1986) were on the order of 3,500 spores m^{-3}, although they did not report any averaging time over which the concentrations were measured or any net exposure data.
- Cultures of bronchoalveolar lavage and serum antibody profiles of Canadian farm workers experiencing acute pulmonary mycotoxicosis (Lecours et al., 1986) revealed possible association with *Aspergillus fumigatus* and *A. nidulans*. The symptoms had completely disappeared within a month, although some alveolitis persisted for six months. No exposure data were presented. Some cultures also suggested an association with *Micropolyspora faeni*.

Salmonella

Salmonella infection in humans occurs primarily via the fecal-oral route (Perino and Stokka, 1999), so aerosolized *Salmonella* is not as likely as food-borne transmission to affect human health. Still, viable colony-forming units (CFU) of *Salmonella* may be present in livestock dust. *Salmonella* is a Gram-negative bacterium that, like others in its class, is susceptible to desiccation when suspended in air. As a Gram-negative bacterium, airborne *Salmonella* would be a source of environmental endotoxin.

Bioaerosols - General

- Seedorf et al. (1998) measured bioaerosols in livestock and poultry houses in northern Europe. Among their findings were:
  a. Measured concentrations of *Enterobacteriaceae* were 1,000-10,000 colony forming units (CFU) m^{-3}. The total bacterial load was 2.7×10^6 CFU m^{-3}.
  b. Endotoxin measured in a poultry house was 50-700 ng m^{-3}.
  c. Fungi measured in cattle, swine and poultry houses were 10,000 CFU m^{-3}.
- In an effort to identify physical features that would serve as predictive indices for human response to organic dust exposure, Edwards (1986) created dust clouds from organic sources associated with immediate and late allergy, nonallergic disease and from “relatively inert” dust sources. Edwards (1986) measured particle-size distributions of the suspended dust (although he distinguished the dust sources according to physical, not *aerodynamic*, particle size) and found no statistically significant relationship between the shape of the distributions and the nature of the health effect.
- Unpublished, preliminary results of research on airway disease in children living in rural communities (Schwartz et al., 2000) has suggested an interaction between endotoxin exposure and infection with respiratory syncytial virus (RSV) as a precursor to the development of asthma.
- The study of Swedish swine workers by Donham et al. (1989) found that symptoms of respiratory impairment were associated with respirable dust, total dust, endotoxin in total dust, and number of microbes in the air of the work environment. Researchers also found a significant dose-response relationship between airborne endotoxin and forced expiratory volume FEV_1.

Odors

Epidemiological and Quasi-Epidemiological Surveys

Epidemiological study of the public health implications of ILO odors is in its infancy. In virtually every case, these studies have drawn *geographical* associations between health impact and nearby ILOs but have not linked alleged health impact with actual exposure data such as Scentometry or olfactometry surveys. The recent article by Wing and Wolf (2000) provides an example of how these studies have been conducted to date.

Wing and Wolf (2000) examined three North Carolina communities near livestock operations under winter conditions (January-February 1999). The nearby livestock production consisted of:

- One 6,000-hd swine finishing facility
- Two dairies with a total milking herd of 300
- One unconfined livestock area with no liquid manure management system

The authors surveyed health symptoms and reduced quality of life in these communities in the context of generic “rural health” and did not identify livestock production as the focal point when recruiting participants. The major finding of the study was that the use of liquid manure management systems (as compared to a pasture operation) significantly increased the incidence of the following symptoms of reduced quality of life:

- Respondents indicated that they were reluctant to open the windows or to go outside

- Respondents reported headache, runny nose and/or sore throat
- Excessive coughing
- Burning eyes

Individuals conducting the surveys did not notice odors on the dates they conducted the surveys, and the authors did not collect environmental exposure data, so no clear association exists between odor *per se* and the physical and psychological symptoms reported. The nature of the psychological responses could suggest odor as [one of] the causative agent(s), but as is the case with much of the survey data concerning the health effects of livestock odors, the conclusions were not buttressed with monitoring data, olfactometry, Scentometry or other exposure measurements. Wing and Wolf (2000) also reported that the survey responses were highly species-specific (ruminant vs. monogastric), but without hedonic tone data and/or species-traceable odorant profiles, the causes and implications of the species-specific responses are unclear.

Chemical characterization

- Zahn et al. (1997) identified 40 organic compounds in liquid and outdoor air samples near a "high odor" swine facility, 27 of which were "confirmed to contribute to decreased air quality" in the area. They associated C2-C9 organic acids (e. g., butyric, propanoic, valeric) with the greatest potential for decreased air quality.
- O'Neill and Phillips (1992) reviewed the literature on odorous compounds associated with livestock wastes and the air around them. They identified 168 such compounds, 30 of which have detection thresholds below 1 $\mu g\ m^{-3}$. Of the ten compounds with the lowest detection thresholds, six were sulfur-containing.
- Bethea and Narayan (1972) identified odorous compounds from a beef cattle confinement chamber under three different manure-handling scenarios. Major odorants included methanol, multiple aldehydes, ethanol, ethyl formate, 2-propanol, indoles and assorted carboxylic acetates and propionates.

Health effects mechanisms

- Schiffman (1998) summarized a number of physiological and psychological health effects that have been traced to the various dimensions of odor (e. g., intensity, frequency, hedonic tone, offensiveness, pungency). Cumulative effects of odorants at sub-threshold concentrations may take the form of olfactory pathway kindling (OPK; temporal summation of sub-threshold stimuli) or long-term potentiation (LTP; enhancement of synaptic processes resulting from high-frequency stimulation). However, Schiffman reported that neither the OPK or LTP hypothesis has been definitively supported by measurements associated with swine operations.
- Schiffman (1998) cited a number of studies from the early 1990s that sub-threshold concentrations of individual odorants produce unique patterns of electrical brain activity and that differences in those neural responses could be traced to differences in hedonic tone.
- Schiffman (1998) identified the anatomical overlap of the olfactory and limbic (emotional) systems as a contributor to mood implications of the pleasantness/unpleasantness dimension of odor perception in humans.
- Wysocki et al. (1997) observed that the perception of acetone odor in acetone-exposed workers (detection threshold 855 ppm) was less sensitive than that of unexposed individuals (detection threshold 41 ppm) by a factor of more than 20. Interestingly, the threshold limit value for acetone is 750 ppm, implying that adaptation and/or sensitization to individual odorants could cause workers to lose their ability to detect threatening concentrations of those odorants and leave the area. Some of these odorants dissolve into body tissues from the blood stream and are re-released over time at detectable levels in the breath into the neighborhoods of sensory receptors.

- Miner (1973) cited research by Barth (1970) that identified two olfactory disorders, anosmia (failure to detect odors; can be partial or complete) and parosmia (sensing an odor other than the one actually presented; is usually temporary).

Conclusions and Recommendations

Ammonia (NH_3)

Among all of the gases emitted by ILOs, ammonia is perhaps the most widely recognized by the general public. Our review of the literature suggests that public concern about ammonia as a primary threat to public health is not scientifically justified. The main findings are that (a) ammonia tends to exist in clinically significant quantities (commonly 5-20 ppm) in mechanically ventilated livestock enclosures but not in naturally ventilated enclosures (unless winds are utterly calm, vents are occluded, or passive ventilation is otherwise disturbed), in open lots or beyond the ILO property line; (b) ammonia at documented ambient concentrations may intensify human health responses to co-pollutants (e. g., particulate matter), and more research is needed to characterize the nature and extent of such synergies and their relation to ILOs; and (c) ammonia is known to contribute to the formation of secondary particulate and thus requires more understanding of its persistence, deposition and PM formation kinetics in relation to sources of atmospheric sulfate, nitrate and chloride near ILOs. In summary, ammonia is significant mainly as an occupational hazard in confined areas, as a synergistic co-pollutant and as a precursor to secondary fine (respirable) particles.

Hydrogen Sulfide (H_2S)

H_2S is second only to (or arguably on a par with) NH_3 in its notoriety with the public. Its implications for human health are real, although like NH_3, concentrations measured downwind of an ILO (i. e., beyond the property line) are usually insignificant. As with NH_3, the main threat of H_2S occurs in fully-enclosed livestock housing. H_2S is a common pollutant emitted by many industrial activities (e. g., pulping mills, petroleum recovery), and the literature is replete with evidence of its hazard to human health. Some literature has suggested that reduced sulfur compounds, including H_2S, are readily oxidized in the atmosphere and therefore dissipate over shorter distances than relatively inert pollutants subjected only to atmospheric dispersion. By itself, H_2S from ILOs is most accurately seen as an occupational hazard but not as a primary threat to public health. Its synergistic potential along with co-pollutants from ILO sources merits additional research. Because it is denser than air, H_2S tends to settle and accumulate in depressions and below surface confined spaces posing an additional risk in enclosed facilities and depressions.

Trace Gases

Although many of the trace gases associated with odors from livestock and poultry production are individually considered hazardous substances or hazardous air pollutants, as individual compounds they do not routinely appear at concentrations that pose a threat to human health. In most cases, measured concentrations in the occupational context are two to three orders of magnitude less than the lowest human health thresholds. Little is known, however, about the nature and extent of interactions between and among these compounds, especially as a mixture of many dozens of them. Assuming strictly additive effects, a cursory analysis (using a commonly accepted risk assessment algorithm, presented as a *hazard quotient*) of a mixture of primary odorants suggested that such a mixture posed virtually no risk to public health, especially in terms of acute health effects. Still, uncertainty about interactive effects and the sheer number of compounds in question suggest that the health implications of long-term exposure to these trace gases remain unclear and in need of further investigation.

Particulate Matter (PM)

Particulate matter effects on respiratory health are many and varied, in large measure due to the wide range of particle size, shape, composition and biological or chemical activity. We found a growing consensus that fine particles (i. e., $<2.5\mu$) pose a significant threat to the long-term pulmonary health of human populations. Coarse-mode particles are not associated as definitively with long-term health effects in humans, but do contribute to short-term allergic reactions and reversible, upper respiratory problems. Primary PM emitted by ILOs, most of which is generated by mechanical shearing or grinding of solids, tends to be dominated by coarse particles. Because fine PM tends to result from chemical processes like combustion, ILOs emit relatively little fine PM except as exhaust from vehicle engines and boilers. The primary source of PM from fully-confined livestock housing is exhaust fans. Open-lot livestock production, such as open-lot dairies and beef feedyards, may generate large quantities of PM from corral surfaces during dry weather patterns. Feed mills and vehicle traffic on unpaved roads produce PM from both open-lot and fully-enclosed facilities. Recent studies of “brown cloud” phenomena in the Rocky Mountain west have implicated ammonia emissions from production agriculture in the formation of secondary fine PM.

Bioaerosols

Viable airborne microbes are ubiquitous. Although ILOs appear to serve as significant sources of airborne microbes, with the exception of molds and fungi, we found little data to suggest that the concentration of viable airborne pathogens is an accurate predictor of human health insult. However, endotoxin from the ruptured cell walls of Gram-negative bacteria is clearly a potent toxin to humans that is responsible for a wide range of related respiratory syndromes.

Research Recommendations.

1. Lipfert (1997) has suggested that “the goal of research on air pollution and health should be to evaluate and communicate…risks so that an informed electorate can make knowledgeable choices for the most appropriate expenditures of public health funds.” There are other compelling motivations for health effects research, but the theme is consistent: when presented with policy and resource-allocation options, disparate stakeholders need to begin with a common basis in credible science. The proliferation of policy options and the pressure to adopt one or more of them is unlikely to abate, which alone sufficiently justifies a coordinated and thoughtful research agenda concerning the health effects of airborne emissions from ILOs.
2. The “Air Workgroup” at the “Confinement Animal Feeding Operation Workshop,” sponsored by the U. S. Center for Disease Control and Prevention and the National Center for Environmental Health (CDC, 1998), concluded that, “non-occupational health effects [of air contaminants] have not been well characterized.” Further, the workgroup affirmed that airborne emissions from large swine facilities may be reasonably thought to represent a threat to public health, although the research literature has not yet defined the extent of that threat or the causative pathways. Finally, the workgroup emphasized that occupational studies should not be applied indiscriminately to the general population because of conditioning, “healthy worker” effect and employee self-selection.
3. Because ambient concentrations of known pollutants (i. e., outside and downwind of ILOs) are not well correlated with indoor concentrations of those pollutants, health effects studies of ILO emissions must account not only for ambient exposures but also indoor exposures. Although it may be appropriate to measure only outdoor concentrations or intensities when quality-of-life complaints arise (e. g., when neighbors are discouraged from hanging clothes out to dry or from enjoying a neighborhood barbecue), most people spend the vast majority of their time indoors such that indoor exposures are the more compelling cause of any observed health effect.
4. Schiffman (1998) has proposed that animal models be developed to mimic human exposures to pollutants emitted by ILOs. Although some authors have documented occasional similarities between the pulmonary responses of humans and livestock, whether livestock species are appropriate candidates for such modeling is still speculative) and should be determined in the near term.
5. The association between endotoxin concentration and the particle size of its PM carriers is muddy and indistinct. Some authors have found an association; others have found none. The ambiguity of the research results thus far suggests that any association is site-specific. Whenever possible, endotoxin researchers should include particle-size fractionation in their sampling schemes so that the site-specific influences that govern these associations can be exposed over time.
6. Although distinctions between livestock species (i. e., with respect to digestive systems, metabolic pathways, feeding regimes, housing facilities and management factors) are frequently and objectively relevant to the nature, quantity and health effects of airborne emissions associated with various

species, agricultural researchers and public health authorities alike should resist the temptation to cast such inter-species distinctions in terms of preference for one species over the other. Such preferences are inherently political questions. Policy makers and other officials need to be aware of the potential for research comparing multiple species to be used in a cynical effort to obscure significant findings rather than illuminate and expose them.

7. Relative to other exposure pathways such as ingestion, dermal absorption and injection, inhalation exposure standards for known ILO emissions are scarce and thinly documented.
8. For epidemiological data on the health effects of odors to be interpreted and compared with other studies, a greater degree of standardization in intensity, concentration and offensiveness measurements and scales is sorely needed. One promising development is the growing adoption of the European standard for forced-choice, dynamic olfactometry, but that development addresses only the intensity dimension of odor. Standardized offensiveness scales would help to establish baselines for the interpretation of, among other things, psychological health data pertaining to nuisance odor.

Table 1. Exposure limits and hedonic tones for a cross-section of known odorants and other constituents associated with emissions from ILOs.

		Exposure Limits (ppm)		**Database**	**Hedonic**
Class	**Constituent**	**Occup.**	**Ambient**	**Citation(s)**	**Tone (a)**
N	Ammonia	25-50	0.15	679; 737; 974; 747	ammoniacal
N	Methylamine	10	n/a	679; 974; 747	fishy
N	Dimethylamine	10	n/a	679; 974; 747	fishy
N	Trimethylamine	10	n/a	679; 974; 747	fishy <100 ppm
N	Indole	n/a	n/a	457; 960	fecal
N	Skatole	n/a	n/a	457	fecal
S	Hydrogen sulfide	10	.03-.05	355; 738	rotten egg
S	n-Propyl mercaptan	1.6 mg m^{-3}	n/a	495	onion
S	Methyl mercaptan	0.5-10	n/a	974	decayed cabbage
S	Butyl mercaptan	10	n/a	974	skunk
S	Dimethyl sulfide	1.0-20	n/a	159; 974	decayed vegetables
S	Dimethyl disulfide	1000 μg m^{-3}	n/a	974	decayed vegetables
VFA	Acetic acid	10	n/a	154; 974	vinegar
VFA	Propionic acid	10	n/a	154; 974	sour
VFA	n-Butyric acid	n/a	n/a	154; 669	sour
VFA	n-Valeric acid	n/a	n/a	457	fecal
VFA	iso-Valeric acid	n/a	n/a	457	rancid cheese
PHN	*p*-cresol	5	n/a	457; 974	creosote
PHN	phenol	19 mg m^{-3}	n/a	154;	medicinal
CHO	Acetaldehyde	100	9 μg m^{-3}	159; 974	fruity
CHO	Acrylaldehyde	0.1	0.02 μg m^{-3}	974	fruity
CHO	Valeraldehyde	175 mg m^{-3}	n/a	974	fruity
CHO	Toluene	375 mg m^{-3}	0.4 mg m^{-3}	974	n/a
CHO	Vinyl acetate	30 mg m^{-3}	0.2 mg m^{-3}	974	n/a
CHO	Dimethyl ketone	2400 mg m^{-3}	n/a	974	sweet
CHO	Methyl ethyl ketone	590 mg m^{-3}	1 mg m^{-3}	159 974	sweet
BDT	Endotoxin	10 ng m^{-3}	80-170 ng m^{-3}	586; 260; 260; 295	n/a

Class

N	Nitrogen-containing
S	Sulfur-containing
VFA	Volatile fatty acid
PHN	Phenolic
CHO	Containing only carbon, hydrogen and oxygen
BDT	Biologically-derived toxin