This publication discusses the sources, factors, and characteristics of dust emissions from cattle-feeding operations.

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With the trend toward larger and more concentrated animal feeding operations (CAFOs), particulate matter (PM) emissions from open-lot CAFOs are an increasingly prominent environmental issue. This is particularly true for CAFOs located in arid and semi-arid climates, where dry conditions favor dust emissions.

Particulate matter, or solid-phase aerosols, may be classified by aerodynamic diameter, which refers to the diameter of a spherical droplet of water that would have the same settling velocity in air as the aerosol particle in question. Fine particles with a mean aerodynamic diameter of about 2.5 micrometers (PM$_{2.5}$) or less may be respired deeply into the lungs. PM$_{2.5}$ is considered a threat to human health because it is associated with respiratory impairment and premature death. The so-called “inhalable” fraction of PM generally consists of particles having a mean aerodynamic diameter less than 10 micrometers (PM$_{10}$) and includes the PM$_{2.5}$ fraction plus a range of coarser particles, sometimes known as PMcoarse, PMc, or PM$_{10-2.5}$. The coarse fraction of inhalable PM generally is associated with reversible human health effects (e.g., allergic reactions) and quality-of-life factors. Fugitive PM from cattle feedyards also may reduce visibility and serve as a carrier for a range of malodorous compounds.

The provenance of aerosols may be classified as primary or secondary. Primary aerosols are generated directly by mechanical (e.g., grinding, scouring) or chemical (e.g., combustion) processes. On a cattle feedyard, the main sources of primary PM are hoof action on uncompacted manure, vehicle traffic on unpaved roads, feed pro-

Figure 1. Dust events generated by open-lot concentrated animal feeding operations may reduce ground-level visibility on nearby roadways. (Photo: S. Sakirkin)
Fugitive dust emissions from open-lot CAFOs are receiving increased regulatory scrutiny.

Secondary PM forms in the atmosphere as a product of acid/base or sunlight-mediated redox reactions. Secondary aerosols associated with CAFOs derive principally from gas-phase ammonia (a base), which dissociates into atmospheric moisture and there reacts with dissolved sulfate, nitrate, and/or chloride ions (all acids) to form fine particles. Because secondary PM tends to form fine to very fine particles, its environmental implications are regional to transnational.

Regulatory Matters

Fugitive dust emissions from open-lot CAFOs are receiving increased regulatory scrutiny, especially in the San Joaquin Valley of California and in southern Arizona, where PM concentrations characteristically exceed federal standards. Currently, odors associated with dust are regulated only under nuisance provisions, in which enforcement is driven either by complaints to the state regulatory authority or by nuisance litigation.

The National Ambient Air Quality Standards (NAAQS) establish threshold concentrations for certain criteria pollutants above which adverse human health effects may be expected in sensitive individuals. Particulate matter is one of those criteria pollutants. As of November 2011, these standards contain three independent, primary (i.e., directed at protection of public health) standards for PM. For PM_{10}, which was first regulated under the NAAQS in 1987, the only remaining standard is a 24-hour average concentration of 150 micrograms PM_{10} per cubic meter (μg/m³). For PM_{2.5}, there are currently two standards, a 24-hour average concentration of 35 μg/m³ and an annual average concentration of 15 μg/m³. Any airshed in which PM concentrations exceed the NAAQS† for any criteria pollutant is classified as a nonattainment area (NAA). At present, southern Arizona and south central California are designated as nonattainment areas for PM_{10}, and central and southern California have a number of nonattainment areas for PM_{2.5}. In both states, the state implementation plan (SIP) for returning to compliance with the NAAQS prominently involves beneficial management practices (BMPs) for agricultural sources, including CAFOs.‡

State air pollution regulatory authorities administer and enforce air pollution regulations. Many states have established their own regulations, which are more stringent than those set by federal agencies. Several states administer programs to monitor ambient air quality, issue operating permits, and conduct compliance inspections and enforcement actions.

Emission Factors and Characteristics

High concentrations of fugitive dust from open-lot CAFOs result from three primary factors. The raw material for dust emissions is uncompacted manure (often mixed with soil) on corral surfaces. The drier that manure is, the more susceptible it is to emission as dust.§ The mechanical energy required to emit the dust is either animal hoof action or wind scouring (Mielke et al., 1974), so elevated concentrations may occur during periods of increased animal activity or during high-wind events. Finally, and perhaps most important, relatively stable atmospheric conditions known as inversions may confine ground-level emissions to a shallow layer of air at the ground level rather than dispersing it to higher elevations through atmospheric turbulence.

Footnotes

† “Violation” of the standard does not mean a single instance of a measurement exceeding the numerical standard; rather, “violation” is defined statistically. In the case of the 24-hour PM_{10} standard, three measurements exceeding the standard within a three-year period constitute a violation of that standard. The statistical provisions for the two PM_{2.5} standards are slightly more complicated.
A diurnal pattern of dust emissions peaking shortly after sunset is commonly observed at many CAFOs in the semi-arid West. This phenomenon, commonly known as the evening dust peak (EDP), results from the temporal coincidence of the three primary factors. First, pen surface moisture is at its daily minimum in the late afternoon to early evening so that dry pen-surface conditions predominate (McCullough et al., 2001). Second, as the sun angle and daytime temperatures decrease, cattle become more active, and the increased hoof action suspends more manure particles in the air. Third, atmospheric stability increases, the boundary-layer mixing height decreases, and winds diminish, reducing atmospheric dispersion. When those three conditions coincide, the peak short-term concentration (e.g., 5- to 30-minute averages) may be 10 to 15 times higher than the 24-hour average (Figure 2).* 

Figure 2. Five-minute average PM$_{10}$ concentrations immediately downwind of the pen area showing the diurnal pattern of the evening dust peak typical of cattle feedyards in the West. Note that these data are not property-line concentrations.

Footnote

*These values of the peak-to-mean ratio are characteristic of open-lot beef feedyards. For open-lot dairies, which feature significantly different patterns of animal behavior and increased shaded area as compared with feedyards, the peak-to-mean ratio is considerably smaller. See Auvermann (2011), “Texas/New Mexico open-lot research,” Proceedings of the Western Dairy Air Quality Symposium, Sacramento, CA, April 20.
Air Quality Education in Animal Agriculture

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References


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Dust abatement plans for cattle feeding operations encompass pen design and maintenance, feeding strategies, water application, and manure management. In general, dust-control tactics for concentrated animal feeding operations (CAFOs) are also effective at controlling odor emissions, particularly in the case of pen-surface management.

**Manure Harvesting**

Regular removal of uncompacted manure from corral surfaces is paramount to reducing dust emissions. Benchtop studies by Razote et al. (2006) have confirmed Auvermann’s (2000) conjecture that the dust potential of a corral surface increases with increasing depth of uncompacted manure. The fundamental reason appears to be that the rear bovine hoof, which is characteristically dragged horizontally across the corral surface — as contrasted with the more vertical motion of the front hoof — accounts for most of the mechanical shearing that resuspends the manure as PM. As the rear hoof penetrates more deeply into uncompacted manure, the mass of manure resuspended in the air increases accordingly. Therefore, reducing the depth of uncompacted material limits the rear hoof’s depth of penetration, limiting dust emissions.

The operational objective of manure-harvesting operations is to keep corral surfaces smooth, firm, and well-drained, maintaining a 1-2 inch thick surface layer of well-compacted manure and soil. A variety of machinery may be used to good effect, with paddle scrapers moving tremendous volumes of manure out of the larger pens and box scrapers collecting smaller volumes of looser, drier material more frequently. Machinery operators should be given a clear picture of the management objective and solid training in machinery settings and operation.

Attentively harvesting manure from pens containing cattle improves pen conditions with little reported effect on cattle performance or stress (Auvermann, 2009). Some feedyards in the southern Great Plains are operating manure-harvesting equipment continually across the yard regardless of the presence or absence of cattle in the pens (Figure 1).

Where the seasonality of farmer demand for manure presents logistical challenges to manure removal, and where pen slopes are sufficient to sustain good drainage without building manure mounds, a year-round composting operation provides an outlet for manure that otherwise would have to be stockpiled in the pens and compacted in place for longer-term storage. When mounds are used for seasonal manure storage and/or enhanced drainage, the manure should be moistened to 20-30 percent and compacted in place by a front-end loader or other wheeled machinery. Track-driven tractors will achieve somewhat less than the desired degree of compaction.

The upper limit on the amount of water that would need to be added to the uncompacted, harvestable manure to reach the 30 percent (wet basis) moisture content conducive to good compaction is about 650 gallons per acre of pen surface per inch of collectable manure depth.
Regular removal of uncompacted manure from corral surfaces is paramount to reducing dust emissions.

**Footnote**


**Manure Harvesting Frequency**

The frequency of manure harvesting from pens is determined by pen conditions, cattle liveweight, feed intake and composition, and stocking density (or its inverse, cattle spacing). Accumulations of uncompacted surface manure should be minimized by frequent harvesting, but care should be taken to maintain a 1- to 2-inch layer of dense, compacted manure and soil above the underlying mineral soil. Harvesting manure too frequently or with poor technique — especially with “push” blades like front-end loader buckets — may damage the underlying layers. This can make future pen surface maintenance difficult, exacerbating odor and dust conditions, and decreasing the fertilizer and/or biofuel value of the harvested manure.

Economic and operational needs also determine the optimal frequency for harvesting manure. Operationally, it is easiest to harvest manure from empty pens rather than occupied pens. Open-lot dairies may have the opportunity daily to harvest manure when the cows head to the milking parlor, but daily manure harvesting is probably not necessary for most dairies.

Pens in beef feedlots, on the other hand, may be continuously occupied for 25 weeks or more. A common practice on many feedlots is to remove accumulated manure from pen surfaces only when cattle are shipped out of the pens. Monitor pen conditions and remove the uncompacted surface layer of manure before it accumulates too deeply — even if pens are occupied by animals. A reasonable threshold depth to trigger box-blade removal of uncompacted manure is 1.5-2 inches.

The depth to which manure is harvested from pens also affects the quality of manure for use as a fertilizer or biofuel. Most fresh manure contains at least 15 percent (dry basis) non-volatile solids (or ash). Over time, organic matter on the pen surface oxidizes to carbon dioxide, thereby increasing the remaining ash content; and hoof action, especially in wetter areas of the pen surface, may mix the manure with the mineral subsoil. In such cases, it is common to observe ash contents from 30 to 70 percent of dry matter in harvested manure (Figure 2).
Mitigation Strategies: Dust Abatement

Ash content is undesirable because it adds weight to manure and decreases the average concentration of active ingredient(s): nitrogen, phosphorous, and potassium for fertilizer, and carbon, hydrogen, and oxygen for biofuel feedstocks. High ash indicates that mineral soil has been incorporated into the manure, which may occur if the machinery penetrates the manure/soil interfacial layer rather than skimming only the uppermost, primarily organic layers.

Manure Harvesting Equipment and Practices

Several kinds of manure removal equipment and different practices may be used to harvest manure from a pen surface. Examples are box blades, front-end loaders, elevating scrapers, and maintainers (followed by box blades and/or loaders). Some practices include scraping and removal; scraping and compaction for temporary in-pen storage; and building manure mounds to enhance pen drainage. The combination of

Figure 2. Although animal behavior and rainfall are the most obvious causes of wallows and holes like the one pictured here, these wallows may have been initiated by poor manure-harvesting techniques breaking into the underlying layers of the pen surface, exposing caliche or clay palatable to the animals, and creating areas from which rainfall runoff cannot drain. (Photo: S. Sakirkin)
The frequency of manure harvesting from pens is determined by pen conditions, cattle liveweight, feed intake and composition, and stocking density or cattle spacing.

Manure harvesting equipment run by trained, skilled operators should be capable of leaving about 1 to 2 inches (2 to 5 centimeters) of hard, smooth, and evenly sloped manure/soil mixture over the underlying mineral soil. Different types of equipment vary in their effectiveness at ensuring rapid drainage and efficient manure removal. Machinery intended for digging or scooping, such as a front-end or bucket loader, may make it more difficult to avoid gouging the pen surface through the underlying compacted layers of manure and soil. Box blades, though having limited capacity and no means of manure removal, are pulled rather than pushed and can be more easily adjusted for penetration depth (Figure 3). Such features allow equipment operators to maintain an optimal pen surface more easily. Once the manure has been stacked by a box blade, a bucket loader is used to remove the manure from the pile.

**Moisture Balance**

The next significant dust-abatement strategy for feedyard surfaces is optimizing the moisture content of the surface manure. Dust predominates when moisture levels are low, and odor potential increases as moisture increases. However, feedyard dust is also associated with odors because some odorous compounds adsorb to the particles (Figure 4). The optimal moisture content for minimizing both dust and odor lies in the range of 25 percent to 45 percent on a wet basis (Sweeten and Lott, 1994).

Water can be applied to pen surfaces, alleys, and unpaved roadways by solid-set sprinkler systems, tank trucks, or water wagons. These systems should be capable of delivering a minimum of two-thirds of a centimeter (¼ inch) of water uniformly across the back 2/3 (i.e., the 2/3 furthest from the feed bunk) of each pen. A study found that solid-set sprinkler systems appear to reduce downwind PM concentrations by 55-80 percent (Bonifacio et al., 2011).

![Figure 3. Box blades are effective at maintaining a smooth, hard pen surface without gouging the interfacial layer and exposing mineral soil. The manure being harvested in this photo will have a higher heating value of about 5,000 Btu/lb as collected and would be considered a relatively high-value biofuel feedstock. (Photo: S. Sakirkin)](image-url)
A survey of 41 feedyards in the southern High Plains found that 54 percent of the feedyards applied water for dust suppression. The most common methods of applying water were water trucks and solid-set sprinkler systems with a couple of feedyards utilizing traveling gun systems. The initial investment, annual fixed, operational, total costs, as well as total cost per head marketed associated with solid-set sprinklers, reel-mounted traveling gun sprinklers, and water trucks for different sizes of feedyards, have been estimated (Amosson et al., 2006; Amosson et al., 2007; Amosson et al., 2008) and are summarized in Table 1. Solid-set sprinklers had the lowest operational cost and were easiest to use because they can be automated. However, they are capital-intensive, especially as a retrofit on existing feedyards.

Water trucks or wagons require less capital outlay and are more versatile for applying water to alleys or roadways, but have higher labor, fuel, and maintenance costs when compared to solid-set sprinkler systems.

A traveling gun system had the lowest total cost of the options analyzed but was less practical than solid-set sprinklers or water trucks. Traveling guns require more management, operate properly only on straight lines of travel, and can temporarily block alleys, interfering with other feedyard operations.

Figure 4. The semi-quantitative relationship between dust and odor potential as a function of manure moisture content on a feedlot pen surface (Auvermann, 2009).
Table 1. Estimated investment, fixed, operational, total annual costs, and total cost in dollars per head marketed for a solid-set sprinkler system, traveling gun, and water truck for different sizes of feedyards.

<table>
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<th>Head Capacity (x 1,000)</th>
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<th>Fixed Cost $/hd Capacity</th>
<th>Operational Cost $/hd Capacity</th>
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¹Assumes annual turnover rate of 2 head marketed per head of one-time capacity.
²Source: Amosson et al., 2006.
³Source: Amosson et al., 2007.
⁴Source: Amosson et al., 2008.

Additional Design Considerations

Good pen design can make manure harvesting and surface maintenance more effective and efficient, which in turn supports reduced emissions of both dust and odor. The shape of a pen should allow for complete manure harvest from edge to edge. Pen surfaces should slope uniformly away from feed bunks/aprons and water troughs at 3-5 percent. Wherever possible, pens should drain discretely into a runoff channel rather than into each other. Pen-to-pen drainage is undesirable because runoff exits the pen area more slowly and creates persistent wet conditions in downstream pens. Those conditions are even more pronounced as hoof action creates manure ridges beneath fencelines, further retarding runoff. Where pen-to-pen drainage cannot be easily avoided, special care should be taken to maintain maximum drainage capacity by eliminating ridges of manure where fencelines cross the drainage channel.

In-pen manure mounding can improve drainage in pens lacking adequate slope and provide livestock with dry areas to rest, reducing hoof traffic in low-lying areas susceptible to damage during wet conditions. In some cases, in-pen mounding may be more economical than stockpiling manure in a dedicated staging area prior to being land applied or composted.

Pen surfaces also may be paved with fly ash or crushed bottom ash, concrete, or a soil/cement blend. Where mineral soil is unpaved, it should be evenly compacted to near Proctor density and should remain undisturbed by animal activity or machinery operations.
Other Dust Mitigation Strategies

Other dust-mitigation options — some potentially effective but still experimental — include:

- Vegetative barriers, such as shelterbelts or windbreaks of one or more rows of tall trees, capture airborne particles and gases on leaf or needle surfaces. Shelterbelts provide the added advantages of reducing erosion and serving as an aesthetic visual screen.⁹

- Increasing stocking density may reduce dust emissions in some cases, but this effect is highly dependent on pen surface moisture and may negatively affect cattle performance (Auvermann and Romanillos, 2000). Still, where unallocated water resources are marginal and seasonal moisture deficits are not extreme, stocking density manipulation may be a cost-effective option to reduce direct water applications.

- Pen surface amendments, such as those effective for dust control on unpaved roadways (usually resins or oils), are being investigated for use on feedyard pen surfaces. This approach may not be cost-effective, because unlike roadways, manure is constantly being added to the pen surface, and any pen surface amendment would require frequent reapplication. In theory, other topical applications of crop residues (e.g., straw, hay, cotton gin trash, or peanut hulls) may reduce evaporation, absorb the energy from hoof action that would otherwise resuspend manure particles, reduce the amount of particulate matter picked up by air currents, and increase the quality of manure for land application or composting.**

- Feed-management techniques that may reduce dust emissions include (a) changing the time of day at which livestock are fed, and (b) changing the fat content in cattle diets. Delaying the last feeding of the day until late afternoon may reduce animal activity during the critical dust-peak conditions near sunset. Increasing fat in cattle diets may increase the cohesiveness of manure, making it more resistant to being pulverized by hoof action.††

- Unpaved roadways and feed mills are other sources of dust emissions found on feedyards. Vehicular traffic on feedyards may take the form of livestock, feed, water, and service trucks. Operating these vehicles at very slow speeds on dry, unpaved roads is helpful in reducing dust emissions. Regular watering of unpaved surfaces at the beginning of the day, prior to the start of heavy vehicular activity, is also useful. The application of resins or petroleum derivatives to caliche, dirt, or stone roadways may be more expensive than frequent watering, but has been shown to be effective at reducing dust emissions from vehicular traffic on feedyards (Gillies et al., 1999).

References


Footnotes

⁹For a more thorough assessment of shelterbelt potential for trapping feedyard dust, see Li Guo, “Measurement and control of particulate emissions from cattle feedlots in Kansas,” PhD dissertation, Kansas State University, 2011.

**Several of these surface amendments have been tested at the benchtop scale for efficacy in feedyard dust control. See Guo, “Measurement and control,” pp. 90ff.

††Increasing dietary fat has not been evaluated on a large commercial scale and has several drawbacks, including (a) reduced feed intake or feed-to-gain performance, and (b) safety concerns for pen riders and their horses working on slick pen surfaces.
Mitigation Strategies: Dust Abatement

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Ammonia (NH₃) is a lighter-than-air, colorless gas with a recognizable pungent smell. It is a source of the essential nutrient nitrogen for plants and animals, but also is classified as a hazardous substance by the U.S. Environmental Protection Agency (EPA). Ammonia occurs naturally and is normally found in trace amounts in the atmosphere where it is the dominant base, combining readily with acidic compounds. It is produced by the decomposition or fermentation of animal and plant matter containing nitrogen, including livestock manure. There is concern about ammonia because of its potential to negatively affect air and water quality, and human and animal health.

Sources and Emissions

Concentrated animal feeding operations (CAFOs) import feed ingredients that contain large quantities of nutrients such as nitrogen. Cattle retain a proportion of the nitrogen they consume, but approximately 70-90 percent is excreted in feces and urine (Cole et al., 2008a). Ammonia is produced by breaking down nitrogenous molecules in manure, such as urea and protein. Urea in urine is rapidly converted to ammonia and is a major ammonia source in manure, while more complex nitrogen-containing compounds, such as proteins, are decomposed more slowly by microbes.

Historically, ammonia was considered a problem only within livestock buildings with inadequate ventilation or poor management. High ammonia levels negatively affect animal health and production, and threaten the health of humans working inside. Correcting ventilation problems and periodically removing animal waste reduces ammonia levels within the building, but these measures do not address the problem of ammonia emissions into the atmosphere. Ammonia emissions to the atmosphere from open-lot CAFOs now also must also be addressed.

Ammonia begins to volatilize (convert to a gas and be lost to the atmosphere) almost immediately after urea is excreted. The loss can continue as manure is handled, stored, or land-applied as fertilizer. As an essential plant nutrient, nitrogen is a primary component of fertilizer; nitrogen lost to the atmosphere from manure by ammonia volatilization is a loss of fertilizer value.

Ammonia in the atmosphere eventually returns to the Earth. Ammonia deposition occurs when ammonia in the atmosphere is deposited as gas, particulates, or in precipitation onto surfaces such as soil or water. Ammonia deposition on nutrient-starved farmlands may be beneficial to crops; however, deposition in sensitive areas may be undesirable.

The complexity of biological and chemical processes, coupled with management decisions, complicates the understanding of ammonia emissions from livestock operations. Differences in livestock digestive systems, diets fed, feed and manure management systems, facility design, location, and weather are just a few of the factors that affect ammonia sources and emissions.
Ammonia in the atmosphere eventually returns to earth. Ammonia deposition in sensitive areas may be undesirable.

Environmental Concerns

Undesirable ammonia deposition may occur locally as dry deposition when ammonia is transferred to sensitive land and water surfaces by air currents or at longer distances as wet deposition. Ammonia deposition can harm sensitive ecosystems when excessive nitrogen stimulates excessive growth of algae in surface waters or weeds in fields or pastures. When algae growth dies, its decomposition consumes oxygen, resulting in hypoxia (low oxygen) in aquatic environments.

For example, the hypoxic “dead zone” near the mouth of the Mississippi River is caused by excess nitrogen and phosphorus carried by the river into shallow coastal waters. This process of eutrophication is characterized by significant reductions in water quality, a disruption of natural processes, imbalances in plant, fish, and animal populations, and a decline of biodiversity.

Sensitive terrestrial ecosystems may experience excessive weedy plant growth, which outcompetes more desirable native species (Todd et al., 2004). Ammonia deposited in soil can undergo nitrification, which converts ammonia to nitrate, which is mobile in water. This chemical reaction lowers (acidifies) the pH of soil (Myrold, 2005). Forests in the humid eastern United States are especially susceptible to soil acidification, which can cause winter injury, loss of tree vigor, and decline of desirable species.

The National Atmospheric Deposition Program (NADP, 2007) and the Clean Air Status and Trends Network (CASTNET) are excellent sources of long-term deposition data. Multiple monitoring stations are located in strategic areas across the United States to monitor and document wet and dry deposition of ammonium, nitrates, and other pollutants. Data from NADP and CASTNET are available online at http://nadp.sws.uiuc.edu/ and http://www.epa.gov/castnet/, respectively.

Human Health Concerns

Ammonia can significantly contribute to reduced air quality when it reacts with sulfur dioxide or nitrogen dioxide in the atmosphere to form aerosols. Aerosols, also known as particulate matter (PM), are atmospheric particles that are classified by the EPA according to their aerodynamic diameter.
Respirable aerosols are particles that can be deeply inhaled into the lungs and have a mean aerodynamic diameter of less than 2.5 micrometers (PM$_{2.5}$). PM$_{2.5}$ poses a threat to human health because it is associated with respiratory symptoms and diseases that lead to decreased lung function and, in severe cases, to premature death (EPA, 2009). Aerosols also reduce visibility in air, diminish irradiance, affect cloud formation, and alter the ozone layer (Romanou et al., 2007; Chin et al., 2009).

Ammonia deposition can contaminate drinking water by increasing the nitrate concentration. This may occur by direct deposition onto water bodies, or indirectly by leaching of nitrogen from soils or erosion of nitrogen-laden soil particles into surface water.

Odor implications of ammonia are localized to regions in the vicinity of the CAFO. Ammonia is easily recognized by its smell, but is seldom associated with nuisance odor complaints near CAFOs any more than other manure constituents such as sulfides, cresols, or volatile fatty acids. Ammonia readily disperses from open lot feedyards and dairies, which helps to reduce its odor intensity to below human detection thresholds. Ammonia odors tend to be more noticeable inside animal barns than in open lots and are greater on or near CAFOs than at more distant off-site locations.

**Measuring Ammonia**

Two categories of air quality measurements are commonly applied to ammonia at or near CAFOs: ambient concentrations and emission rates. Ambient concentrations are measurements of the ratio of ammonia to air in the atmosphere, usually measured in parts per million by volume (ppmv), parts per billion by volume (ppbv), or micrograms per cubic meter (μg/m$^3$). Accurate measurement of the atmospheric concentration in a large mass of dynamic, open air is difficult and requires special instrumentation and/or significant labor inputs.

Emission rates quantify ammonia flux from surfaces to the atmosphere and are reported in units of mass per unit area per unit time as in kilograms per square meter per day (kg/m$^2$/day), and also in units of mass per unit animal per unit time such as kilograms per thousand head per year (kg/1000 hd/yr).

Measurement of ammonia emissions from nonpoint sources such as CAFOs is also difficult because once produced, ammonia quickly volatilizes and is dissipated by air currents. Quantifying ammonia flux from the feedyard surface to the atmosphere relies on direct measurement using fast-response instrumentation, or on a flux model, which attempts to accurately predict the dispersion of gases and particulates through turbulent air. Further, emissions will vary depending on the type of surface (pens, lagoons, buildings) and the nature of processes at individual facilities.

**Regulatory Issues**

**Federal reporting requirements (EPCRA)**

Ammonia emission is regulated under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and the Emergency Planning and Community Right-To-Know Act (EPCRA). In December 2008, the EPA published a final rule that exempted CAFOs from reporting ammonia emissions under CERCLA. However, under EPCRA [40 CFR §355 App A], CAFOs are required to report ammonia emissions in excess of 45 kilograms (100 pounds) per day. Despite the challenges in accurately measuring ammonia emissions from CAFOs, an estimate of the lower and upper bounds can be calculated based upon animal headcounts and research-based figures for average emission rates per head. Noncompliance with the EPCRA ammonia emission reporting requirements could result in fines of $37,500 per day, criminal charges, and up to five years imprisonment.

Ammonia emissions may be indirectly addressed by federal and state regulations aimed at PM$_{2.5}$ concentrations such as those in the National Ambient Air Quality Standards (NAAQS). Because ammonia is a precursor to PM$_{2.5}$, it may be necessary to
Few state regulations currently are directed at ammonia emissions from animal agriculture.

Reducing ammonia emissions to obtain a reduction in PM$_{2.5}$ concentrations. Few state regulations currently are directed at ammonia emissions from animal agriculture. In 2003, California’s Senate Bill 700 removed the reporting exemption from agricultural sources, and in 2006, Idaho put into force its “Permit By Rule” program requiring dairy farms with the capacity to produce more than 100 tons of ammonia annually to comply.

Except for Idaho and California, existing agricultural state regulations of ammonia are aimed primarily at the distribution, storage, and land application of anhydrous ammonia fertilizer. However, states can directly address ammonia emissions in PM$_{2.5}$ non-attainment areas in any case in which ammonia has been shown to be a significant contributor to PM$_{2.5}$ concentrations. In some states, general air quality regulations are based on atmospheric concentrations, and in other states they are based on actual emissions similar to those stipulated by EPCRA. However, atmospheric concentrations and ambient emissions of pollutants like ammonia are not well correlated. How these existing air quality regulations will be applied to livestock ammonia sources in the future is unknown.

**Ambient Concentrations at Cattle Feedyards**

The determination of atmospheric concentrations of ammonia requires highly sophisticated and expensive equipment, considerable labor, and much time. Measurements must be taken over large areas and extended periods, including all annual seasons, to represent the large spatial and temporal variability.

*Figure 2. Estimated contributions of various U.S. ammonia sources based on the National Emissions Inventory (EPA, 2008).*
Other factors that must be reported include a detailed description of the facility, the animals, management practices, on-site weather, and sampling height. Data collected on atmospheric ammonia concentrations at CAFOs vary considerably, but tend to exhibit a 24-hour pattern, with daytime concentrations greater than those observed at night. Ammonia concentrations at cattle feedyards have rarely been observed over 3 ppm.

A variety of methods are available to measure atmospheric concentrations of ammonia, each with a unique set of advantages and disadvantages.

Gas washing, denuders, and passive samplers provide average ammonia concentrations over relatively long periods of 1 to 4 hours. Gas washing is useful for calibration and standardization, but is labor intensive. Fourier-transformed infrared (FTIR) spectroscopy, laser spectrometry, ultraviolet differential optical absorbance spectroscopy (UVDOAS), and chemiluminescence allow collection of nearly real-time measurements and relatively short periods of 5 seconds. Open-path lasers, UVDOAS, and FTIR have the added advantage of integrating measurements over distances from 50 to 500 meters. Dust concentration in the vicinity of feedyards tends to be high, so special measures must be taken when sampling for atmospheric ammonia to avoid errors. Examples of these special measures include installing Teflon® filters preceding detectors, or shortening measurement path lengths.

**Emission Rates from Cattle Feedyards**

An estimated 64-86 percent of total global anthropogenic ammonia emissions come from CAFOs (Baum and Ham, 2009; EPA, 2008; Becker and Graves, 2004; Battye et al., 1994). Of the CAFO emissions, roughly 43-48 percent come from cattle operations (EPA, 2008; NRC, 2003; Battye et al., 1994). Figure 2 presents a graphic illustration of the relative contributions to ammonia emissions by various U.S. sources, based on the National Emissions Inventory (EPA, 2008). This inventory considered ammonia emissions based on ammonia emission factors and county-level populations of livestock intentionally reared for the production of food, fiber, or other goods, or for the use of their labor. The livestock included beef cattle, dairy cattle, ducks, geese, horses, poultry, sheep, and swine.

There is extensive literature regarding ammonia emissions from swine and poultry facilities, but relatively little comprehensive research on large, open-lot beef cattle feedyards (Todd et al., 2008). Methods for estimating ammonia emissions from area sources such as feedyards include mass balance, micrometeorology, flux chambers, wind tunnels, and dispersion models (Hristov et al., 2011). The accuracy and applicability of these estimation methods vary greatly. For example, flux chambers and wind tunnels are appropriate for comparing treatments or assessing relative emission rates, but not for quantifying actual emissions (Cole et al., 2007a; Paris et al., 2009; Parker et al., 2010). Dispersion models all rely on specific assumptions that are often challenged by the feedyard environment and can induce error in emission estimates (Flesch et al., 2005, 2007). Mass balance restraints are necessary to set an upper bound on emission estimates.

Calculating a total nitrogen balance for a facility, which involves determining the amount of nitrogen imported and exported from a feedyard and assuming that unaccounted nitrogen is mostly ammonia, can provide reasonable estimates of ammonia emissions (Bierman et al., 1999; Farran et al., 2006; Cole and Todd, 2009). This is because the majority of gaseous nitrogen loss to the atmosphere is in the form of ammonia, as opposed to nitrous oxide, nitrogen gas, or nitrogen oxides (Todd et al., 2005).

Comparing estimates obtained by multiple methods with calculations from a complete nutrient balance, and local atmospheric concentration data can minimize errors. However, this approach is site-specific and impractical for the purpose of regulatory monitoring at every livestock operation.

Micrometeorological methods such as eddy covariance (EC) and relaxed eddy accumulation (REA) are ideal for feedlots because they provide measurements of
Figure 3. Developing a process-based model requires research inputs from multiple disciplines to estimate ammonia emissions.

Because so many variable and interactive system components must be considered, using a single emission factor is inadequate to predict ammonia rates.

ammonia flux for large areas without disturbing the emitting surface. EC involves high frequency measurements using a fast-response analyzer, accounting for vertical air movements and the mixing ratio of ammonia in the air. REA is an adaptation of EC in which samples from air moving vertically are accumulated over time and analyzed with slower-response analyzers.

The most common method currently used by regulatory agencies to estimate ammonia emissions from CAFOs is to multiply a research-based emission factor by the number of animals on location. However, a single emission factor is not appropriate because ammonia emissions are affected by multiple, complex, and dynamic environmental variables. Therefore, the National Research Council (NRC, 2003) has recommended a process-based modeling approach over the use of emission factors. Process-based models are based on the physical, chemical, and biological processes that contribute to emissions, and take into account dynamic variables such as weather conditions, management practices, and technologies. Thus, they are applicable to a wide range of feedyard situations.

Research Needs

Statistical, empirical, and process-based models are available to estimate ammonia emissions from CAFOs. Statistical models are usually based on data collected from a particular location and provide estimates that may not be appropriate for a different site. Empirical models are commonly built from data collected under controlled conditions and predict well only when those particular conditions exist. Process-based (also known as mechanistic) models apply chemical and physical principles to a theoretical model of a real system, such as a CAFO. Their ability to predict ammonia emissions depends on how well the model represents real processes and the accuracy of important process factors used as inputs in the process-based model.

Many cross-disciplinary factors are considered in the construction of a process-based model, such as animal nutrition, feedyard management strategies, environmental aspects, and meteorological factors (Figure 3). Process-based models of emissions from CAFOs often begin by describing the effects of diet and facility management on nutrient excretion by the animals. In the case of nitrogen, the various chemical forms, routes, and processes the nitrogenous molecules undergo as a feed constituent consumed and excreted by animals is described. Next, the nitrogenous manure...
Issues: Ammonia

constituents are accounted for and partitioned into several pools. Depending on the facility, these pools may include feces, urine, pen surfaces, manure stockpiles, effluent lagoons, and so forth. Finally, the chemical and physical transformations, transfer, and equilibria that occur during manure storage, handling, treatment, and export in each of the several cases are modeled. The model may then be used to predict ammonia emissions.

Models must consider atmospheric ammonia phases, which include gaseous ammonia (NH₃), fine particulate ammonia ([NH₄]₂SO₄ and NH₄NO₃), and liquid ammonia (NH₄OH) as clouds or fog. The transition between these three phases depends on other inconstant atmospheric constituents. Therefore, the proportion of the phases relative to one another is also continually changing. Ammonia readily forms strong hydrogen bonds with water and will attach to many surfaces. Therefore, most materials exposed to air containing ammonia will absorb or adsorb ammonia compounds. In a CAFO environment, gaseous ammonia is prevalent and attaches to the airborne particulate matter emitted from the facility.

The dynamic nature of the atmosphere and its constituents results in significant variations in ammonia concentrations with respect to time, location, and height above the ground. Increasing the distance from the emission source can result in decreasing ammonia concentrations, with the rate of decrease depending on other factors such as air temperature, relative humidity, or wind speed. Dry deposition rates proximate to the CAFO also can decrease with respect to distance, and range widely, depending on atmospheric conditions and emission rates.

Measuring Emissions

It is difficult to measure ammonia emission rates from open-lot CAFOs. Ammonia tends to collect inside sampling instruments, adversely affecting measurement. Open-lot CAFOs have lower ammonia concentrations than those typical of facilities with livestock housing, so more sensitive instrumentation is required. There is relatively little data on ammonia emission rates, flux rates, or emission factors from open-lot beef cattle facilities.

Despite sampling challenges, changeability of ammonia concentrations, and scarcity of data, the average daily ammonia concentrations observed at several facilities by different researchers are consistent. Table 1 presents ammonia concentrations observed at several commercial feedyards in different studies conducted at different times of the year.

Table 1. Ammonia concentrations (ug/m³) measured at commercial open-lot beef cattle feedyards. Adapted from Hristov et al., 2011.

<table>
<thead>
<tr>
<th>Study</th>
<th>Time</th>
<th>Location</th>
<th>Mean or Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hutchinson et al., 1982</td>
<td>April-July</td>
<td>Colorado</td>
<td>290 - 1,200</td>
</tr>
<tr>
<td>McGinn et al., 2003</td>
<td>May</td>
<td>Canada</td>
<td>66 - 503</td>
</tr>
<tr>
<td></td>
<td>July</td>
<td></td>
<td>155 - 1,488</td>
</tr>
<tr>
<td>Todd et al., 2005</td>
<td>Summer</td>
<td>Texas</td>
<td>90 - 890</td>
</tr>
<tr>
<td></td>
<td>Winter</td>
<td></td>
<td>10 - 250</td>
</tr>
<tr>
<td>Baek et al., 2006</td>
<td>Summer</td>
<td>Texas</td>
<td>908</td>
</tr>
<tr>
<td></td>
<td>Winter</td>
<td></td>
<td>107</td>
</tr>
<tr>
<td>McGinn et al., 2007</td>
<td>June-October</td>
<td>Canada</td>
<td>46 - 1,730</td>
</tr>
</tbody>
</table>
When estimating ammonia emissions from open-lot beef cattle facilities, several components of the CAFO system must be considered. Emission factors fail to account for effects of particular components included in process-based models, such as animal diet and age, air and surface temperatures, time of year, geographic location, and many others. So many variable and interactive system components must be considered that using a single emission factor is inadequate to predict ammonia emission rates (Hristov et al., 2011).

Processed-based models, which describe physical processes mathematically as opposed to statistically, are better suited to this task than emission factors. A single ammonia emission factor based primarily on European data proposed by the EPA (2005) is 13 kg/hd annually for feedlot cattle or 23 percent of the total amount of imported nitrogen. This EPA report also estimates the following nitrogen losses as ammonia: 1) stockpiles — 20 percent of nitrogen entering, 2) storage ponds — 43 percent, and 3) land application — 17-20 percent. Because European beef systems vary greatly from U.S. systems, these values may not apply to U.S. feedlot systems.

Studies conducted at North American feedyards using a variety of measurement methods observed a wide range of emission and flux (quantity per unit area per unit time) rates. Reported emission factors ranged between 18 and 104 kg/hd annually, and flux rates ranged from 3.6 to 88 μg/m²/s. Most studies also noted seasonal or 24-hour patterns in ammonia flux rates (Hristov et al., 2011). Reported losses from runoff holding ponds ranged from 3-70 percent of the N entering the pond. Other sources of ammonia loss on beef cattle feedyards include compost piles, which have been estimated to lose 10-45 percent of the N entering the compost (Hristov et al., 2011).

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This publication discusses ammonia abatement measures and when they can be implemented in livestock production.

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Abatement Measures

Ammonia abatement measures can be implemented at two different stages of livestock production. First-stage measures are applied in the pre-excretion stage. These include nutrition-based strategies to reduce the amount of nitrogen excreted in livestock manure. In the second or post-excretion stage, management strategies are implemented to reduce the amount of ammonia transferred to the environment from the manure by agricultural operations.

Nutritional Ammonia Abatement Methods

One means of reducing ammonia emissions from concentrated animal feeding operations (CAFOs) is to reduce the amount of nitrogen excreted by the animals, especially the quantity excreted as urea in urine. Urinary pH also can affect ammonia emissions (Cole et al., 2008a). In some cases, it is possible to manipulate nutritional intake to reduce total nitrogen and urinary nitrogen excretion while continuing to meet the nutritional requirements and performance expectations of the animals. Based upon consistent observations among researchers over the past decade, annual ammonia losses from beef cattle feedyards tend to be approximately half of the nitrogen consumed by cattle, and summer emission rates are about twice those in winter (Todd et al., 2009).

Table 1 presents ammonia-nitrogen loss as a percentage of fed nitrogen for beef cattle feedyards in the Great Plains. Ration composition can be modified in a variety

<table>
<thead>
<tr>
<th>Study</th>
<th>Summer</th>
<th>Winter</th>
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<tr>
<td>a</td>
<td>40</td>
<td>10</td>
</tr>
<tr>
<td>b</td>
<td>50</td>
<td>15</td>
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<tr>
<td>c</td>
<td>60</td>
<td>20</td>
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<tr>
<td>d</td>
<td>70</td>
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<td>e</td>
<td>80</td>
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<td>f</td>
<td>90</td>
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<td>i</td>
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<td>j</td>
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<td>55</td>
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<tr>
<td>k</td>
<td>140</td>
<td>60</td>
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<td>l</td>
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<td>65</td>
</tr>
<tr>
<td>m</td>
<td>160</td>
<td>70</td>
</tr>
<tr>
<td>n</td>
<td>170</td>
<td>75</td>
</tr>
</tbody>
</table>

Reducing the amount of nitrogen excreted by livestock is one way to reduce ammonia emissions.

of ways to effectively reduce ammonia emissions by 20-50 percent with only small effects on animal performance (Cole et al., 2005, 2006a; Todd et al., 2006). Some of the nutritional factors that can be manipulated include crude protein and/or degradable intake protein concentrations (including phase feeding), fat concentration, fiber source and concentration, cation-anion balance (CAB), as well as some growth-promoting feed additives and implants. However, the large size of many CAFOs presents economic and logistic challenges when modifying diets or feeding practices. Modifications to equipment, diets, or management practices may impose increased cost, labor, and time, for example (Figure 1).

Crude Protein

The concentration of protein in feed, as well as its ability to be degraded in the rumen, may affect the quantity and route of nitrogen excretion by beef cattle (Cole et al., 2005). Beef cattle consume dietary crude protein in two forms. The first is degradable intake protein (DIP), which is processed by microbes in the rumen and either absorbed from the rumen (normally as ammonia) or converted to microbial protein and nucleic acids. The second is undegradable intake protein (UIP), which escapes digestion in the rumen and passes to the intestine where it is digested and absorbed as amino acids (approximately 80 percent) or excreted (approximately 20 percent). In general,
as nitrogen consumption increases, urinary nitrogen excretion also increases. Further, as the ratio of DIP to UIP increases, urinary nitrogen excretion also increases. Dietary changes must be made carefully and with consideration to unintended consequences. If, for example, in an attempt to lower ammonia emissions the dietary protein intake is reduced below the nutritional needs of the animal, the growth rate may be slowed, the animal will require more days on feed to reach market weight, and the cumulative ammonia emissions from a feedlot may actually increase. In addition, making changes to decrease ammonia emissions may potentially result in the increase of other undesirable emissions such as nitrous oxide.

In closed chamber laboratory (Cole et al., 2005) and artificial pen surface (Todd et al., 2006) experiments, decreasing the crude protein concentration of beef cattle finishing diets based upon steam-flaked corn from 13-11.5 percent decreased ammonia emissions by 30-44 percent. Ammonia fluxes from an artificial feedyard surface were reduced by 30 percent in summer, 52 percent in autumn, 29 percent in spring, and 0 percent in winter (Todd et al., 2006). The research team concluded that despite requirements to maintain cattle performance, reducing crude protein in beef cattle diets may be the most practical and cost-effective way to reduce ammonia emissions from feedyards. Another study by Todd et al. (2009) determined that feeding high concentrations (> 20 percent) of wet distiller’s grains, which are becoming increasingly available as a ration component, increased crude protein intake in beef cattle and resulted in increased ammonia emissions.

**Phase Feeding**

As beef cattle mature, they require less dietary protein. Phase feeding involves adjusting nutrient intake over time to match the changing needs of the animal. If protein is not progressively diminished through the feeding period in balance with the animals’ nutritional requirements, potentially more nitrogen is excreted and more ammonia may be emitted from the facility (Cole et al., 2006a; Vasconcelso et al., 2009). Studies on cattle fed high-concentrate, steam-flaked corn-based diets have suggested that a moderate reduction (~1.5 percent) in dietary crude protein (CP) in the final 28 to 56 days of the feeding period may decrease ammonia emissions by as much as 25 percent, with little adverse effect on animal performance (Cole et al., 2006a). Based on seven cooperative studies to determine the effect of crude protein on ammonia emissions and animal performance (Cole, 2006b), a reduction of dietary crude protein from 13 percent, which is optimal for growth, to 11.5 percent resulted in a 3.5 percent decrease in average daily gain and an approximate 30 percent reduction in ammonia emissions. Therefore, in certain economic conditions, it may be practical to accomplish a significant reduction in ammonia emissions with a minimal effect on animal performance.

**Distiller’s Grains**

Distiller’s grains have recently been introduced into beef cattle rations and may affect CAFO ammonia emissions. Research by Cole et al. (2008b) reported that a 10 percent increase in distiller’s grains in rations based upon steam-flaked corn increased manure production by approximately 10 percent. In rations based upon dry-rolled corn, the same increase in distiller’s grains resulted in a 0-7 percent increase in manure production. In both cases, the concentration of nitrogen in the manure was not affected. The combination of increased manure volume and steady nitrogen concentrations may result in potentially greater ammonia emissions. In a comparison of ammonia emissions at two feedyards, Todd et al. (2009) found that one feedyard feeding distiller’s grains averaged 149 g NH₃-N head⁻¹ d⁻¹ over nine months, compared with 82 g NH₃-N head⁻¹ d⁻¹ at another feedyard feeding lower protein, steam-flaked corn-based diets.

**Fiber**

Manipulation of dietary fiber also may affect ammonia emissions from feedyards. In a study by Erickson et al. (2000), dietary fiber in the form of corn bran was increased in cattle finishing diets. During the winter-spring study period, nitrogen volatilization rates were decreased, but animal performance was adversely affected.
As beef cattle mature, they require less dietary protein. Phase feeding involves adjusting nutrient intake over time to match the animal’s changing needs.

In another study by Bierman et al. (1999), beef cattle were fed different diets containing wet corn gluten feed (WCGF), corn silage, and alfalfa hay. The researchers concluded that dietary fiber and carbohydrate source affected the way feed was digested and excreted by cattle, resulting in changes to the amount of nitrogen excreted. Nitrogen excretion was highest for cattle fed a ration based on WCGF, but these cattle also had the highest performance.

Farran et al. (2006) manipulated alfalfa hay and WCGF in beef cattle diets and made similar observations. Increasing alfalfa hay or WCGF intake resulted in an increase in nitrogen intake, nitrogen excretion, nitrogen volatilization, and cattle performance. They further concluded that recovery of nitrogen in the manure and finished compost was also increased, especially in the case of WCGF, as a result of increased organic matter content in the manure.

**Cation-Anion Balance**

Ammonia emissions are inhibited in low-pH environments, and lowering dietary cation-anion balance (DCAB) can potentially lower the pH of cattle urine. Thus, notwithstanding other factors, lowering the pH of cattle urine may potentially reduce CAFO ammonia emissions. However, Erickson and Klopfenstein (2010) noted no effect of DCAB on nitrogen volatilization losses. Lowering urine pH may have little effect on ammonia emissions because the pen surface of feedyard pens may have significant buffering properties that strongly resist pH changes, tending to maintain a pH of approximately 8 or higher (Cole et al., 2009). Furthermore, cattle performance may be reduced by low-DCAB diets (Cole and Greene, 2004).

**Post-Excretion Ammonia Abatement Methods**

Post-excretion ammonia abatement strategies, such as improving manure management, can reduce the rate of nitrogen volatilization and ammonia emissions. Animal health considerations in post-excretion methods are not as great a concern when compared to nutritional methods. However, some manure management strategies, such as pen scraping, can be beneficial for animal health. Manure contains nitrogen and phosphorus, both of which contribute to the value of manure as a fertilizer. Nitrogen volatilization can reduce the nitrogen:phosphorus ratio to below most plant requirements, thereby reducing the fertilizer value of the manure and requiring a greater land application area to avoid excessive phosphorus applications. Reducing ammonia emission rates from manure will enhance the fertilizer value of manure and lower ammonia emissions. Besides manure management, manipulating other factors such as the pH and moisture content of soil and/or manure also can affect ammonia emissions (Cole et al., 2008a).

**Urease Inhibitors, Zeolites, Fats, and Other Pen Surface Amendments**

Based upon laboratory studies, a number of compounds can potentially be applied to feedlot pen surfaces to reduce ammonia emissions from feedyard surfaces (Varel, 1997; Varel et al., 1999; Shi et al., 2001; Parker et al., 2005; Cole et al., 2007). Substances such as zeolites (a microporous, aluminosilicate mineral), fats, and urease inhibitors such as N-(n-butyl) thiophosphoric triamide, cyclohexylphosphoric triamide, and phenyl phosphororidiamidate may change manure properties such as pH, ammonia adsorption potential, or hydrolysis potential, which in turn affects ammonia emission rates.

Urease inhibitors work by slowing down or blocking the hydrolysis of urea (found in urine) by the enzyme urease (found in feces). However, urease inhibitors must continually be applied to manure because they rapidly degrade (Powers, 2002; Parker et al., 2005). Application of some compounds such as fats may be accomplished indirectly via dietary supplementation. Zeolites and urease inhibitors have been shown to decrease ammonia emissions when applied as a surface amendment, but not when used as a dietary amendment (Varel, 1997; Varel et al., 1999; Shi et al., 2001; Parker et al., 2005; Cole et al., 2007). Both dietary and surface amendments of fat appeared to
decrease ammonia emissions (Cole et al., 2007). The dietary fat effect is likely because a proportion of fed fat is voided onto the feedyard surface after being excreted in undigested form by feedyard cattle. No significant effects on animal performance were observed.

**Lowering pH**

One of the most important factors involved in ammonia emissions from surfaces is the pH of the emitting medium. In general, ammonia volatilization rates increase with pH. Therefore, lowering the pH of soil or manure can reduce ammonia emissions. With acidic conditions, given a constant temperature, more nitrogen will remain in the form of ammonium (NH$_4^+$), thereby decreasing the amount of ammonia available to volatilize. A significant reduction in ammonia emissions has been observed with acidifying amendments such as aluminum sulfate (alum), ferrous sulfate, phosphoric acid, or calcium salts.

Maintaining the low pH can be challenging, however, because manure may have a strong buffering capacity, which results in the pH eventually returning to a more basic level and a resumption of ammonia emission. Strong acids are more cost-effective than weak acids or acidifying salts, but they are more hazardous and, therefore, are not suitable for use in agricultural environments (Ndegwa et al., 2008).

**Manure Harvesting, Storage, and Application**

Frequent pen cleaning may help to capture nitrogen in the manure by decreasing loss to the atmosphere. Research in Nebraska (Erickson and Klopfenstein, 2010) revealed that cleaning pens once per month, as opposed to once after every 166-day feeding period, reduced apparent ammonia nitrogen losses by 24 percent. The effectiveness of the monthly cleaning strategy varied seasonally, being less in winter. This may be due to the accumulation of nitrogen that occurs in the pen surface manure pack during the winter, apparently the result of decreased ammonia losses during the colder months (Cole et al., 2009). In addition, the amount of nitrogen collected in the manure was 50 percent greater from pens cleaned monthly.

Covering manure to reduce its exposure to elements such as sun, wind, and rain is very effective at reducing ammonia emissions from storage areas. When manure is land-applied, immediate incorporation or injection into the soil has been shown to significantly reduce ammonia losses when compared to broadcasting alone (Ndegwa et al., 2008).
Frequent pen cleaning may help capture nitrogen in the manure by decreasing loss to the atmosphere.

References


Mitigation: Ammonia Abatement


Hydrogen sulfide (H₂S) is a naturally occurring, colorless gas with a foul smell like rotten eggs. It is often produced when sulfurous compounds in organic matter, such as manure, are decomposed by bacteria in anaerobic (without oxygen) conditions. It also occurs in natural gas, groundwater, and volcanic gases. Common anthropogenic sources of hydrogen sulfide include sour crude oil refineries, pulp and paper mills, oil and gas operations, sewage treatment plants, and animal agriculture.

Hydrogen Sulfide Sources on Beef Feedyards

In general, hydrogen sulfide emissions from concentrated animal feeding operations (CAFOs) come from two sources. The first source is treatment lagoons or runoff retention structures. Anaerobic decomposition of manure in these structures produces hydrogen sulfide gas.

The second source is surfaces where manure accumulates, such as in pens, alleys, or manure storage areas. Extended anaerobic conditions on these surfaces, which are normally associated with standing water or wet manure, can generate this gas over large areas.

“Purple sulfur bacteria,” which use carbon dioxide, hydrogen sulfide, and ammonia for cell growth, thrive in such conditions and may be easily detected by their distinctive color (Figure 1). Although purple lagoons are less likely to be considered an odor nuisance than...
lagoons of other colors, data have shown little difference in sulfide concentrations (Koelsch et al., 1997).

Cattle consume sulfur in their feed and drinking water, and absorb it into their bodies primarily as sulfide. It is an essential nutrient for ruminants, but when sulfur is consumed in excess of dietary requirements, it is excreted. According to the National Research Council (NRC), cattle require at least 0.15 percent of sulfur on a dry matter basis (dm), and can tolerate up to 0.40 percent. Water in some areas may contain sulfur levels as high as 2,000 mg/L. Feed rations containing wet distillers grains plus solubles (WDGS) balanced for energy exceed the NRC requirements for sulfur, because sulfuric acid is added to grain during the ethanol production process, making WDGS higher in sulfur content than the feedstocks it substitutes. It has been estimated that every 1,000 head of beef cattle consume about 25 to 42 kg of sulfur daily in the Texas Panhandle. Cattle retain 10 to 20 percent of the sulfur they consume — that means 80 to 90 percent of ingested sulfur is excreted.

Hydrogen Sulfide and Human Health

Hydrogen sulfide is highly toxic at elevated concentrations. Exposure can occur by inhalation of contaminated air or ingestion of contaminated water. Breathing air with high levels of hydrogen sulfide may cause immediate death, and exposure to low levels over a long period can cause headaches, fatigue, and eye irritation. Hydrogen sulfide is heavier than air and may accumulate in enclosed or low-lying areas.

According to TOXNET, a federal database of information on hazardous substances, more than 80 percent of humans can smell hydrogen sulfide at concentrations between 0.5 to 30 ppbv (parts per billion by volume). The irritant threshold (the concentration at which classic irritation symptoms begin to appear in 83 percent of the population) begins at 25 ppmv (parts per million by volume) and is well above human detection levels (the concentration at which 83 percent of humans can detect the gas by smelling it).

Humans cannot detect hydrogen sulfide at levels above 150 ppmv because it paralyzes the olfactory nerve, disabling the sense of smell. Some health effects from exposure to hydrogen sulfide, such as damage to the olfactory nerve, are potentially reversible. However, anosmia (inability to perceive odors) and respiratory damage may be chronic, and damage to the eyes or brain is often permanent.

Human exposure to high levels (around 100 ppmv) will instantly cause lung damage, respiratory failure, and unconsciousness. Complete nervous-system failure and sudden death result at very high levels (around 800+ ppmv).

Short-term exposure to moderate concentrations of hydrogen sulfide (between 1 to 10 ppmv) will cause eye, nose, and throat irritation, nausea, dizziness, breathing problems, headaches, loss of appetite, and problems sleeping. Extended exposure will irritate breathing passages and may lead to pulmonary edema (fluid buildup in the lungs). People living near hydrogen sulfide sources such as paper mills, refineries, geothermal features, or meat-packing plants have an increased risk of eye irritation, geothermal features, or meat-packing plants have an increased risk of eye irritation, cough, headache, nasal blockage, and impaired neurological function.

Chronic exposure to even very low levels of hydrogen sulfide may cause health effects (Von Essen and Auvermann, 2005). Exposure over a period of time to levels below the irritant threshold can result in physiological symptoms such as eye or respiratory irritation, and neuropsychological symptoms such as depression, memory loss, anxiety, sleep disruption, numbness, loss of balance, and fatigue (Legator et al., 2001).

Some officials are concerned that hydrogen sulfide concentrations downwind of feedyards may exceed regulatory or public-health limits. However, a recent literature review (Auvermann and Rogers, 2000) and field monitoring near and within cattle feedyards (Koelsch et al., 2004) concluded that concentrations measured downwind of concentrated animal feeding operations are usually very low. Hydrogen sulfide can be emitted at very low rates by open-lot beef cattle feeding facilities (feedyards) in gaseous form from pen surfaces and runoff retention structures. The main threat of hydrogen sulfide arises in enclosed housing structures or below-grade, enclosed manure-storage pits, features not generally found on beef feedyards.

Footnote 1

1 “Lagoon” refers to a pond that is designed and operated for treatment of organic wastes, by which we mean biochemical stabilization via digestion of volatile solids (VS) and reduction of biochemical oxygen demand (BOD). In contrast, “runoff retention structures” are designed only for detention (short-term) storage, not treatment. Consequently, the emergence of a dominant population of purple sulfur bacteria in lagoons is a management objective, but for runoff retention structures such an event may indicate the pond is under designed.
Environmental Concerns

Because it oxidizes rapidly to sulfuric acid in the presence of water, hydrogen sulfide may corrode structural steel or concrete, causing it to fracture or fail altogether. Severe damage in municipal wastewater systems across the United States prompted the Environmental Protection Agency to produce a technical handbook aimed at detecting and controlling hydrogen sulfide corrosion. It is well known for causing corrosion of equipment, pipes, and fittings in water, oil, and gas production wells.

Hydrogen sulfide, which is found throughout pulp and paper mills, also may result in extensive damage to electronics in control systems. Biogenic sulfide corrosion of concrete is an increasingly pervasive problem in wastewater systems, including manure storages. Corrosion due to hydrogen sulfide is not generally a problem in feedyards in the semi-arid High Plains because the gas is present at very low levels, relative humidity is low, and most feedyards do not have closed structures where the gas can accumulate.

Regulatory Issues

Due to its toxicity, hydrogen sulfide is subject to state and federal regulations. Reporting requirements fall under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and the Emergency Planning and Community Right-to-Know Act (EPCRA). In December 2008, feedyards were exempted from reporting hydrogen sulfide releases under CERCLA, but EPCRA [40 CFR §355 App A] requires feedyards to report hydrogen sulfide releases in excess of 45 kilograms (100 pounds) per day.

Cattle headcounts in excess of approximately 11,750 trigger EPCRA reporting requirements. Producer organizations, such as Beef USA and the National Cattlemen's Beef Association, have provided research-based guidelines to feedyards for estimating and reporting hydrogen sulfide releases.

Federal regulatory values for hydrogen sulfide are health-based standards pertaining to occupational exposure. A ceiling limit is a maximum permissible concentration limit that must never be exceeded. The Occupational Health and Safety Act (OSHA) has established an acceptable 10-minute ceiling limit for hydrogen sulfide of 20 ppmv, and the National Institute for Occupational Safety and Health (NIOSH) recommends a 10-minute ceiling limit of 10 ppmv. Feedyards are not exempt from OSHA and NIOSH ceiling limits unless they meet employment-based criteria (29 CFR §1904.2(b)(2)).

The Texas Administrative Code (30 TAC §112.31-32) sets two thresholds for locations downwind of a hydrogen sulfide source. The first threshold is an urban standard of a net, ground-level concentration of 0.08 ppmv (parts per million by volume) averaged over any 30-minute period at any residential, business, or commercial property. The second threshold is a rural standard of a net, ground-level concentration of 0.12 ppmv averaged over any 30-minute period, which applies to any other type of property. Accordingly, the Texas Commission on Environmental Quality (TCEQ), which enforces the thresholds specified in the TAC, established regulatory values for a 30-minute average ambient concentration of 0.08 ppmv downwind of sources, including feedyards.

Thirty-five states have regulations pertaining to ambient air concentrations of hydrogen sulfide, but only five of those clearly require compliance by CAFOs: Iowa, Minnesota, Nebraska, Rhode Island, and Texas. Table 1 presents the criteria for each of those five states. CAFOs are clearly exempt from hydrogen sulfide ambient air concentration regulations in 15 states because they are specifically exempted, not defined, or not included as an industry. These states include Alabama, Arizona, Colorado, Delaware, Hawaii, Illinois, Louisiana, Maryland, Michigan, Missouri, Montana, New Hampshire, New Mexico, North Dakota, North Carolina, Pennsylvania, South Carolina, Tennessee, Vermont, Wisconsin, and Wyoming. The applicability of existing regulations to CAFOs is unclear in the remaining 15 states.

Human health, welfare, or property protection are common rationales for establishing specific hydrogen sulfide ambient air concentrations. Some states derive their

Footnotes 2 and 3

2Feedyards that employ 10 or less non-family workers are exempt from OSHA record-keeping requirements, but remain subject to reporting requirements.
3“Net concentration” refers to the numerical increase in concentration between a measurement upwind of a source and a corresponding measurement downwind of that source.
4“Ambient concentration” refers to an absolute measurement, usually at a location that does not isolate a single source but represents the broader area around the monitoring site.
Hydrogen sulfide is highly toxic at elevated concentrations. Exposure can occur by inhalation of contaminated air or ingestion of contaminated water.

The EPA also derived a chronic inhalation reference value (RfC) of 0.001 ppmv for hydrogen sulfide, to which some states applied uncertainty factors and then based their regulations on the more stringent value. Other states, such as Iowa, use data from local monitoring studies and health data to establish regulatory levels. North Dakota established its levels from a literature review on hydrogen sulfide. Others, such as New York and California, base their levels on odor thresholds. Property damage from the corrosive effect of hydrogen sulfide on buildings and structures is the rationale for levels set by Nebraska and Pennsylvania.

Due to its strong, distinctive smell, hydrogen sulfide is sometimes chosen as a surrogate for regulation of odor. Minnesota, New York, Hawaii, and Texas base their regulations in part on nuisance odor abatement. For example, the Minnesota Pollution Control Agency (MPCA) currently regulates feedlot nuisance odor by limiting hydrogen sulfide emissions as measured at the property line of the feedyard (Ambient Air Quality Standards, MR7009.0080, 18 April 2000). Table 1 presents hydrogen sulfide ambient air concentration standards currently regulated by five different states.

### Monitoring Methods

Compliance monitoring of hydrogen sulfide concentrations requires continuous monitoring according to established protocols with approved instrumentation (Figures 2, 3, and 4). Instruments must be regularly inspected and calibrated by knowledgeable personnel to ensure accurate measurements. Many scientific instruments are capable of measuring hydrogen sulfide, including Dräger Tubes®, Jerome Hydrogen Sulfide Analyzers, and pulsed fluorescence analyzers.

One of the more common, portable instruments is the Jerome Meter 631-X® (Arizona Instrument LLC, Chandler, AZ). It can detect hydrogen sulfide from 2 ppbv to 50 ppmv. In a Jerome meter, sulfur compounds adsorb to a gold film sensor, whose resistivity varies with adsorbed sulfur molecules. The change in resistivity corresponds to a total reduced sulfur (TRS) value, which includes trace amounts of other sulfur compounds such as dimethyl sulfide, dimethyl disulfide, diethyl disulfide, and methyl...
mercaptan. Because some of those trace compounds are also present at feedyards, actual hydrogen sulfide concentrations reported by a Jerome meter are biased slightly upward. The degree of the bias depends on the concentration of other sulfurous compounds in the air.

Another instrument used to measure hydrogen sulfide is a pulsed fluorescence analyzer. The electronic hydrogen sulfide analyzer is capable of detecting the gas between 3 ppbv and 100 ppmv. This instrument is designed for use in a laboratory or other protected environment (such as a mobile instrument shelter), but with a protective housing and adequate power supply it also can be used in the field. This instrument catalytically converts hydrogen sulfide to sulfur dioxide and then measures the sulfur dioxide concentration with a pulsed fluorescence analyzer. If background sulfur dioxide is present, these analyzers must be operated in differential mode by bypassing the catalytic converter with a second sampling tube. Other gases present at feedyards, such as ammonia, may interfere with hydrogen sulfide measurements.

Dräger Safety Inc. (Telford, PA) makes the Dräger Tube, which detects hydrogen sulfide gas by drawing an air sample through a glass vial filled with a reagent. The reagent changes color to indicate the presence of hydrogen sulfide gas, and the length of the color change along the tube indicates the concentration. Different models of Dräger Tubes use various reagents to detect hydrogen sulfide gas at specific ranges. For example Model 0.2/b uses mercuric chloride (HgCl₂) to detect concentrations between 0.1 and 6 ppmv, while Model 2/a uses a mercuric ion (Hg²⁺) to detect concen-

**Figure 2.** Several gas analyzers operating inside a trailer deployed at a concentrated animal feeding operation including two hydrogen sulfide analyzers (Model 450i, left rack, second from top; Model 45C, left rack, third from top) by Fisher Scientific (Waltham, MA). (Photo: K. Casey)
Thirty-five states have regulations pertaining to ambient air concentrations of hydrogen sulfide, but only five of those clearly require compliance by CAFOs: Iowa, Minnesota, Nebraska, Rhode Island, and Texas.

Other gases may interfere with hydrogen sulfide readings, depending on the model of the instrument and the reagent used.

Other hydrogen sulfide monitoring equipment includes microprocessor-based electrochemical sensors, which can be used for personal protection in areas where hydrogen sulfide gas may exist. These instruments are smaller, portable, and can be mounted near equipment, clipped to a belt, or carried in hand. Primarily used as an early warning device to alert users when they should vacate an area, they are not designed for precise concentration measurements or regulatory compliance monitoring. When gas concentrations exceed a predetermined threshold, the instrument emits a visual and/or audible alarm. Examples of this type of instrument include the MSA Altair Pro® and the Dräger Pac III®.

What We Know

Data concerning hydrogen sulfide emissions from feedyards and runoff retention structures are scarce, especially prior to 2003. Koelsch et al. (2004) used Jerome meters to monitor three feedyards in Nebraska for one week in the spring, summer, and fall. The weekly average hydrogen sulfide point concentrations downwind of the pens ranged from 0.0006 to 0.013 ppmv among the three feedyards. The data revealed a diurnal pattern (daily cycle), with higher concentrations occurring during warmer afternoons.

Another researcher, See (2003), also reported evidence of a diurnal pattern of hydrogen sulfide emissions in a study measuring hydrogen sulfide concentrations downwind of a Texas feedyard in June 2000. In this study, the 15-minute average hydrogen sulfide concentrations downwind of both the pens and the runoff retention structures were on the order of 0.005 ppmv.

Rhoades et al. (2003) measured hydrogen sulfide concentrations upwind and immediately downwind of feedyard pens and runoff retention structures at three different Texas feedyards during one year. Averaging times were approximately 10 minutes. Average concentrations downwind of pens ranged from 0.004 to 0.104 ppmv, and downwind of the runoff retention structures ranged from 0.003 to 1.075 ppmv. Because all of the readings were taken during the day and diurnal emission patterns are suspected, the concentrations reported by Rhoades et al. (2003) may not be representative of daily averages.

Figure 3. An intake port mounted on the roof of a trailer deployed at a concentrated animal feeding operation provides air samples to hydrogen sulfide analyzers inside the trailer. The pen surfaces and runoff retention structure visible in the background are potential sources of hydrogen sulfide. (Photo: K. Casey)
A fourth study (Koziel et al., 2004) measured ambient hydrogen sulfide concentrations using an electronic analyzer stationed on the west side of a Texas feedyard. The data are not considered representative of downwind ambient concentrations because the wind was variable, and the position of the analyzer was not always downwind. Koziel et al. reported mean hydrogen sulfide concentrations of 0.030, 0.003, and 0.035 ppmv for fall, winter, and spring, respectively. None of the above studies reported ambient 30-minute average hydrogen sulfide concentrations in excess of the state of Texas regulatory value (0.08 ppmv).

Data on hydrogen sulfide emission rates from feedyards are limited. No published data are available on direct measurements of the emissions from runoff retention structures. Attempts have been made to measure hydrogen sulfide fluxes from feedyard surfaces using a Jerome meter, but the concentrations were below the detection limit of the instrument (Duyson et al., 2003).

One study in Minnesota (Wood et al., 2001) reported a mean hydrogen sulfide emission rate of 103 μg/m²/min from a feedyard surface. Two other studies (Baek et al., 2003; Koziel et al., 2005) used a flux chamber and electronic hydrogen sulfide analyzer to measure emission rates from pen surfaces at different feedyards. Baek et al. (2003) reported an emission rate of 1.88 μg/m²/min, and Koziel et al. (2005) reported 1.39 μg/m²/min.

Equilibrium flux chambers have been shown to underestimate hydrogen sulfide concentrations in comparison with other methods such as backward calculating dispersion models. These computer models begin with observed concentrations and weather data, and then calculate backward to estimate hydrogen sulfide emission rates. Ambient downwind hydrogen sulfide concentration data collected by Rhoades et al. (2003) and Galvin and Parker (2005, unpublished data) were entered into two backward calculating dispersion models. The WindTrax® model (Thunder Beach Scientific, Edmonton, AB) uses a backward Lagrangian stochastic (bLS) algorithm, while Ausplume® (Environmental Protection Agency, Victoria, Australia) uses a Gaussian algorithm.

There was a significant discrepancy between the predictions two models generated and what was experimentally observed using flux chambers by Baek et al. (2003) and Koziel et al. (2005). The models predicted emission rates from feedyard pens ranging from 3.6 to 3.7 kilograms per day per 1,000 head, which was approximately 100 times greater than the flux-chambers measurements. Using overall mass-balance calculations as the reference point, the dispersion models yielded more plausible flux estimates than the flux-chamber studies.
It now appears that hydrogen sulfide emissions from cattle feedyards are a matter of intermittent bursts rather than a continuous flux.

Figure 5. Ambient hydrogen sulfide concentration (30-minute average) observations from July through September, 2008, juxtaposed with Texas regulatory values.

What We Are Learning

Most of the available data on hydrogen sulfide emissions from feedyards has been collected from intermittent spot measurements with Jerome meters. These data do not provide information about diurnal or seasonal variations in hydrogen sulfide emissions. Recent continuous monitoring by Casey et al. (unpublished data) of ambient hydrogen sulfide levels at a feedyard in the Texas Panhandle provided insight into the diurnal and seasonal emission rates and shed light on the uncertainty of hydrogen sulfide measurement methods. Air samples were collected every minute from 3.3 meters above a feedyard pen surface and measured using a TEI H2S analyzer. Ambient hydrogen sulfide concentrations in the pen area were recorded continuously from March 2007 to July 2010. Almost all of the 30-minute average concentrations were below the TCEQ level of concern (0.08 ppmv).

The long-term average concentration in the center of the feedyard was 0.005 ppmv, which is close to the detection limit of the instrument. Significant peaks in hydrogen sulfide emissions were observed after one rainfall event, but no peaks were observed after subsequent rainfall events. While flux per unit area was often higher from runoff retention structure surfaces, cumulative mass emissions from the pen surfaces were much greater due to their larger surface area. Figure 5 presents ambient hydrogen sulfide concentrations (30-minute average) from a feedyard located in the Texas Panhandle through July and September 2008 (Casey et al., unpublished data).

Results from the pen area indicated that ambient hydrogen sulfide concentrations were generally low, with an average of 4.2 ppbv between March and June of 2008. Occasionally the levels spiked for short periods of time. A diurnal trend was evident as hydrogen sulfide emissions tended to increase with warmer air temperatures.

New research is attempting to explain these peaks and learn more about the factors that affect hydrogen sulfide emission rates. Some factors being investigated include ambient temperature, precipitation events, changes in barometric pressure, cattle activity, the amount of hydrogen sulfide held in the manure matrix, and differences in ration formulation. It now appears that hydrogen sulfide emissions from cattle feedyards are a matter of intermittent bursts rather than the more continuous fluxes associated with ammonia gas (NH3), for example.
References


### Additional Resources


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