



Atmospheric Ammonia: Sources and Fate

A Review of Ongoing Federal Research and Future Needs

Air Quality Research Subcommittee Meeting Report

(Notes from the October 1999 meeting of the CENR Air Quality Research Subcommittee)

Prepared by

**COMMITTEE ON THE ENVIRONMENT AND NATURAL RESOURCES
AIR QUALITY RESEARCH SUBCOMMITTEE
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INTRODUCTION

Gaseous ammonia has long been known to play a key role in atmospheric chemical processes and, following deposition, in the biogeochemical processes that occur in sensitive ecosystems (forests, soils, streams, and coastal waters). Ammonia also reacts rapidly with atmospherically-formed sulfuric and nitric acids to contribute to ambient levels of fine particles. The need to better understand the role of this important air pollutant has been underscored in recent years as ammonia emissions from intensive animal production facilities are on the increase and the Nation works to craft effective management strategies for fine particles in an effort to mitigate concerns over public health impacts and to enhance visibility in pristine areas of the country.

The October, 1999 meeting of the Air Quality Research Subcommittee of the CENR focused on a discussion of Federal research related to atmospheric ammonia. This report provides a brief summary of the current state of science as discussed at the meeting, with the addition of some material that was not presented at the meeting due to time constraints. A list of research needs resulting from this discussion is also provided. The presentation materials used by the various speakers and some additional supporting material is provided in the Appendices to this report.

A complete and comprehensive review of the science related to atmospheric ammonia is clearly beyond the scope of this report. Rather, the report provides a brief overview of the science, identifying key knowledge and capability gaps, and is intended as an information piece to guide the development of future Federal research programs.

Emissions

Current estimates of ammonia emissions to the atmosphere are characterized by a high degree of uncertainty. Agriculture represents the largest source of ammonia emissions. The diverse nature of agricultural operations and the fact that there are only a limited number of studies designed to quantify emission and activity factors in this sector have contributed to this uncertainty.

In a recent report¹ (EPA National Air Pollution Trends Update, 1970-1997) the U.S. EPA provides an estimate of the distribution of ammonia emissions by sector for the year 1997. The data are presented in Figure 1. Based on these estimates, the agricultural sector contributes approximately 85% of U.S. ammonia emissions.

¹ EPA National Air Pollution Emissions Trends Update, 1970-1997 (1998)
(<http://www.epa.gov/ttnchie1/trends97/infochief.html>)

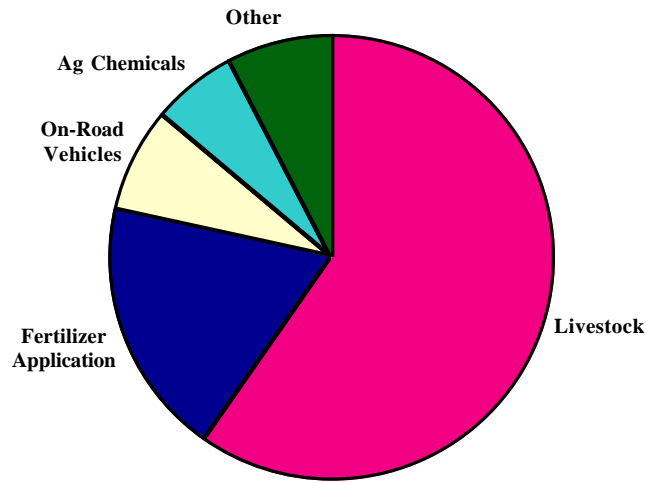


Figure 1. Total annual U.S. emissions of ammonia by sector. EPA National Air Pollution Emissions Trends Update, 1970-1997 (1998)¹

The importance of agriculture as a contributor to the Nation’s ammonia emission inventory is also evident in the emission density map for 1997 provided below. States with extensive animal-rearing operations (cattle, hogs, and poultry) are among those with the highest emission densities.

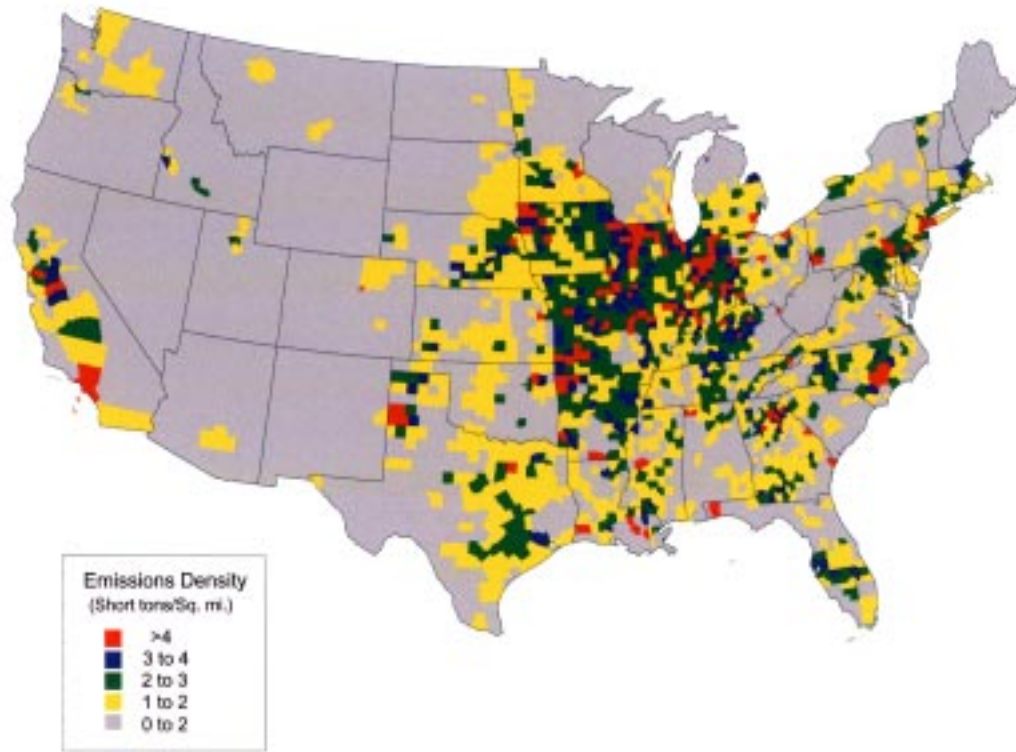


Figure 2. Map of 1997 U.S. ammonia emission density, by county. EPA National Air Pollution Emission Trends Update, 1970-1997 (1998)

Agricultural Emissions:

Ammonia emissions from agricultural operations present three major environmental issues:

- Odor – Ammonia has a strong and unpleasant odor, resulting in complaints from residents adjacent to large-scale animal rearing operations.
- Habitability – Ammonia at high levels is toxic to animals (including humans). Therefore, control of ambient ammonia levels in breeding facilities is a priority.
- Air Quality – The role of ammonia in the production of fine particles and the deposition of biological available nitrogen is the focus of this report.

During the meeting, Henry Tyrrell (USDA) gave an overview of the major agricultural sources of ammonia, which result primarily from intensive animal husbandry operations such as dairy operations and rearing facilities for beef cattle, hogs and poultry. Only about 10% of the nitrogen in feed for beef cattle is converted to meat; the rest is excreted in animals feces (~30% N) and urine (~60% N). Dairy cattle are somewhat more efficient, but about 35% of total N is still lost via the urine. In these operations, ammonia is produced when urea that is present in the urine is mixed with the urease enzyme, primarily in the feces. The N in urine is particularly volatile, and much of it ends up in the atmosphere, although 90% of the nitrogen in lagoon-stored manure also volatilizes. The amounts of ammonia emitted become highly daunting when agricultural statistics are taken into account. In 1998, there were approximately 34 million beef cattle, 9 million dairy cows, 60 million pigs, 7.6 million sheep and lambs, and over 400 million chickens being raised for meat, milk, eggs, etc. Even these large numbers are dwarfed by broiler chickens – 7.6 billion last year. This number of animals produces substantial ammonia emissions – about 10,000 metric tons NH₃/day.

James Ferguson (University of Pennsylvania) discussed potential adjustments to livestock production practices to reduce NH₃ from dairy operations. Reducing feed protein can reduce production of urea, which is all converted to NH₃. Other approaches include reducing conversion of urea to NH₃ by inhibiting urease and inhibiting volatilization of NH₃ by acidifying until land application. The particular type of enclosure developed for the University of Pennsylvania's experimental dairy cattle herd is, however, a very open one that encourages complete release of gases produced therein.

Susan Thorneloe and Larry Jones (EPA) discussed EPA research to quantify ammonia emissions from agricultural operations. Sampling campaigns have been conducted at a large hog farm using an open-path Fourier transform infrared (OP/ FTIR) spectrometer to measure NH₃ from several sources. An initial series focused on the seasonal variability of emissions from the finishing barns. Measuring across the exhaust fans has yielded estimates of these emission rates. Very limited data exist in the literature for emissions from swine finishing barns. Van Der Hoek² presents an emission factor used by the

² Van Der Hoek, K., Estimating ammonia emission factors in Europe: summary of the work of the UNECE ammonia expert panel, Atmospheric Environment, vol. 32, pp. 315-316, 1998.

European Community (EC) as 2.89 kg/hog/yr (7.9 g/hog/day). Extending the EPA data to a similar yearly value by averaging the seasonal data suggests an emission factor of 3.69 kg/hog/yr, with an individual seasonal range of 2.74 - 4.75 kg/hog/yr. A difference of less than 25% is noted between the two emission factors. The EPA estimates may present an upper bound to the emission factor. The data have been collected during daylight, and one would expect that waste production would be reduced at night, so the integrated daily emission factor should be less. The much higher path-average concentration noted when westerly winds bring the plume from the nursery and farrowing barns through the path suggests that these sources also need to be examined. Van Der Hoek² used an emission factor three times higher for sows in these facilities. A detailed concentration mapping around the farm conducted during the winter season suggests that the finishing barns have 6 times the emissions of the farrowing operations because of the much larger number of animals in the finishing barns. The data from the lagoon reflect a low winter emission as reported by other researchers.

The impact of the barns locally and regionally may be affected by the thermal buoyancy of their plumes. With a 15-20°C differential between the barn plume and the ambient winter temperature, a condensation-defined plume could be visibly traced rising quickly above the 20-30 m tree canopy and, thus, moving off-site. In the summer, EPA measurements indicated little buoyant plume rise when no temperature difference existed between the barns and the ambient. One would expect that ecological interactions on or near the farm site would be more likely because the plume remains near the ground.

An analysis of the EPA data suggests that the bulk of the ammonia emissions from the swine operations comes from the barns (50%) with lesser amounts coming from lagoons (37%) and the spray application of animal waste (13%).

Pierce and Bender³ have recently presented estimates of U.S. ammonia emissions from livestock operations. Their calculations were based on USDA agricultural statistics⁴ and emission factors from Battye et al.⁵ These data (Table 1) indicate that cattle represent the largest single source of livestock emissions, with hogs a distant second.

³ Pierce, T.E., and L.W. Bender, Examining the temporal variability of ammonia and nitrogen oxide emissions from agricultural processes, presented at AWMA/EPA Emissions Inventory Conference, Raleigh, North Carolina, October 27, 1999. (http://www.epa.gov/asmdnerl/awma_ei99.pdf)

⁴ USDA Agricultural Statistics. (<http://www.nass.usda.gov/census/>)

⁵ Battye, R., W. Battye, C. Overcash, and S. Fudge, Development and selection of ammonia emission factors. (<http://www.epa.gov/ttn/chief/efddocs/ammonia.pdf>)

Table 1. Estimates of annual ammonia emissions from livestock for 1997. (Pierce and Bender, 1999)

Category	Census (x 10 ⁶)	Emission Factor Kg NH ₃ /animal	Total Emission x 10 ⁶ kg NH ₃
cows	99.0	22.9	2267
hogs	61.2	9.2	563
layers-pullets	367.0	0.18	66
broilers	1037.2	0.18	187
turkeys	104.3	0.86	90
sheep	7.8	3.4	27
Total			3200

Ammonia Emissions From On-Road Vehicles:

Ninety five percent of U.S. automobiles are equipped with 3-way catalysts for control of nitrogen oxide pollutants. These catalysts operate by constantly oscillating the air-to-fuel ratio in the engine between oxidation and reducing conditions to simultaneously control hydrocarbon, carbon monoxide (CO), and nitrogen oxides (NO_x) emissions. Under reducing conditions, the catalyst may also produce ammonia. The EPA has instituted a limited study of the dynamics of ammonia formation by instrumenting an automobile and driving it on-road to determine ammonia as a function of operating modes. EPA is particularly interested in ammonia formation during computer commanded fuel enrichment, and is still investigating instrumentation that can give real-time output. To date they have done some limited static testing and a few on road measurements.

Measurements have been made with the instrumented vehicle in park, in the parking lot, using H₂SO₄ bubblers and a continuous chemiluminescence analyzer. The results indicated emission concentrations ranging from 5 to 55 ppm. Based on these results, on-road measurements were made over a 24-mile trip using the H₂SO₄ bubblers. The on-road measurements indicated an average emission rate of 0.24 gm/mile and would imply that ammonia emissions are in the range of NO_x emissions. Additional information on ammonia emissions from individual vehicles is provided in Table 2 and in a recent paper by Becker et al.⁶

⁶ Becker, K.H., J.C. Lorzer, R. Kurtenbach, P.Wiesen, T.E. Jensen, and T.J. Wallington, Nitrous oxide (N₂O) emissions from vehicles, *Environmental Science and Technology*, **33**, 4134-4139, 1999.

Table 2. Ammonia emissions from catalyst-equipped vehicles.

Data Source	Ammonia Emissions) (gm./mi)
EPA Trends Report	0.1
1981 Buick	0-0.2
1983 OMS Average	0-0.5
1984 Volkswagen	0-0.14
1993 Chevrolet Lumina	
Parking Lot	0.03-0.14
Route I-40	0.24

Measurements made inside roadway tunnels provide another source of data on ammonia emissions from on-road vehicles. These studies are statistically quite robust since the measurements are representative of the thousands of vehicles that pass through the tunnel during the periods of measurement. Two such studies are discussed below.

In 1993, Fraser and Cass⁷ measured ammonia levels in the Van Nuys tunnel in Los Angeles during the morning rush hour. These authors estimated ammonia emissions from dual bed and three-way catalyst-equipped vehicles in on-road operation to be 72 mg km⁻¹ (0.12 g mi⁻¹) or 480 mg L⁻¹. When combined with fuel usage data for the South Coast Air Basin, the emission estimates translated into a total of 24 tons day⁻¹ of ammonia for on-road vehicles. This represents approximately 13 percent of the total ammonia emissions for the region surrounding Los Angeles.

In 1999, Kean et al.⁸ used measurements from the Caldecott Tunnel in the San Francisco Bay area to estimate emissions of NO_x, CO, and ammonia for a fleet of primarily gasoline-powered light-duty vehicles. These authors reported the ammonia emissions from this fleet to be 475±29 mg L⁻¹. This result is in excellent agreement with the previous estimate of Fraser and Cass.

It is important to note that, during the period between these two studies, the State of California instituted regulations to reduce the sulfur content of auto fuel. Sulfur in gasoline is known to poison the three-way catalysts that are used in cars and light duty trucks. The California regulations were designed to improve NO_x-removal efficiency in an effort to reduce ozone and fine particle levels. As EPA has moved to reduce the sulfur content of gasoline nationally, concern has been raised that improved catalyst performance might result in an increase in ammonia emissions from on-road vehicles. The similarity of the ammonia emission factors obtained for fleets with very different

⁷ Fraser, M.P., and G.R. Cass, Detection of excess ammonia emissions from in-use vehicles and the implications for fine particle control, *Environmental Science and Technology*, **32**, 1053-1057, 1998.

⁸ Kean, A.J., R.A. Harley, R.F. Sawyer, D. Littlejohn, D. Zucker, and G.R. Kendall, On-road measurement of ammonia and other motor vehicle exhaust emissions, presented at the 10th CRC On-Road Vehicle Emissions Workshop, San Diego, California, March 27-29, 2000.

fuel sulfur levels (more than an order of magnitude) argues against an adverse impact on ammonia emissions.

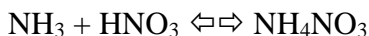
Ammonia “Slip” in Power Plants:

Nitrogen oxide control technology for power plants is another area where there has been concern that an emission management strategy that targets one pollutant (NO_x) may have the unintended effect of increasing emissions of another pollutant (ammonia). The level of NO_x control that EPA is calling for from power plants to reduce ozone levels in the eastern U.S will require the use of Selective Catalytic Reduction (SCR) and Selective Non-Catalytic Reduction (SNCR) systems. Both of these technologies require the addition of ammonia as part of the NO_x -control process.

Tom Feeley (Department of Energy) evaluated the significance of ammonia emissions resulting from the application of SCR and SNCR technologies in response to the 22-state NO_x SIP call. DOE’s “worst case” analysis concluded that the application of these NO_x -control technologies would result in 5100-8700 tons yr^{-1} additional ammonia emissions in the 22-state region. These emissions would represent approximately one quarter of one percent of current U.S. ammonia emissions.

ATMOSPHERIC CHEMISTRY

Fred Fehsenfeld (NOAA) discussed the role of ammonia as a major contributor to secondary aerosol formation in the atmosphere. Ammonia reacts rapidly with both sulfuric and nitric acids to form fine particles.



Reaction of ammonia with sulfuric acid or ammonium bisulfate is favored over reaction with nitric acid. Thus, in most of the U.S. the majority of aerosol ammonium is associated with sulfate ion. However, significant amounts of ammonium nitrate are formed in regions where sulfate levels are low and ammonia and nitrogen oxide emissions are high (e.g., Southern California and the Mountain West). The ammonium nitrate formed is thermally unstable and in dynamic equilibrium with ammonia and nitric acid. Since sulfate aerosols deposit much more slowly than either ammonia or nitric acid, the formation of ammonium sulfate aerosol serves to distribute the ammonia/ammonium over a much larger region than occurs when nitrate aerosol is formed.

Results from recent laboratory and field studies⁹ suggest that ammonia actually promotes the nucleation of sulfuric acid in the atmosphere. This effect is not well understood and results in rates of particle nucleation in the atmosphere that appear to be much faster than expected based on current theory.

DEPOSITION

Once released into the atmosphere, ammonia is returned to the surface as either gaseous ammonia or as an ammonium ion. The ammonium ion can be associated with nitrate, sulfate, or some other anion and incorporated into an aerosol or as part of the ionic mix found in cloud and raindrops.

The deposition of ammonia gas is an extremely complex process. The analysis of data collected during studies of ammonia transport and deposition^{10,11} suggests that atmospheric ammonia is in dynamic equilibrium with growing vegetation. There apparently is a “compensation point” related to the partial pressure of ammonia in leaf tissue of plants. The surface is a sink for ammonia when the ambient concentration exceeds the compensation point. The surface is a source when ambient levels are below the compensation point. The absorption/desorption of ammonia from vegetation and soils is not included in most air quality models, which certainly contributes to the uncertainty in estimates of ammonia/ammonium transport and deposition.

Estimates of dry deposition of ammonium ion can be obtained from the aerosol deposition estimates produced by EPA’s Clean Air Status and Trends Network (CASTNet) and NOAA’s Atmospheric Integrated Research Monitoring Network (AIRMoN) networks. Ammonia deposition estimates are obtained as weekly averages.

Ammonium deposited in precipitation is quantified as part of the interagency National Atmospheric Deposition Program/National Trends Network (NADP/NTN). Ammonium ion concentration in precipitation throughout the U.S. is shown in Figure 3. The spatial distribution is strikingly similar to the ammonia emissions distribution shown in Figure 1, suggesting that local ammonia sources have a significant impact on broad regional patterns of ammonium wet deposition.

⁹ Weber, R.J., P.H. McMurry, R.L. Mauldin, D.J. Tanner, F.L. Eisele, A.D. Clarke, and V.N. Kapustin, New particle formation in the remote troposphere – A comparison at various sites, *Geophysical Research Letters*, **26**, 307-310, 1999.

¹⁰ Galbally, I.E., G.D. Farquhar, and G.P. Ayers, in: Cycling of Carbon, Nitrogen, Sulfur, and Phosphorous in Terrestrial and Aquatic Ecosystems, J.R. Freney and I.E. Galbally, Eds. (Springer-Verlag, Berlin) pp. 1-9, 1982.

¹¹ Langford, A.O., and F.C. Fehsenfeld, Natural vegetation as a source or sink for atmospheric ammonia: A case study, *Science*, **255**, 581-583, 1992.

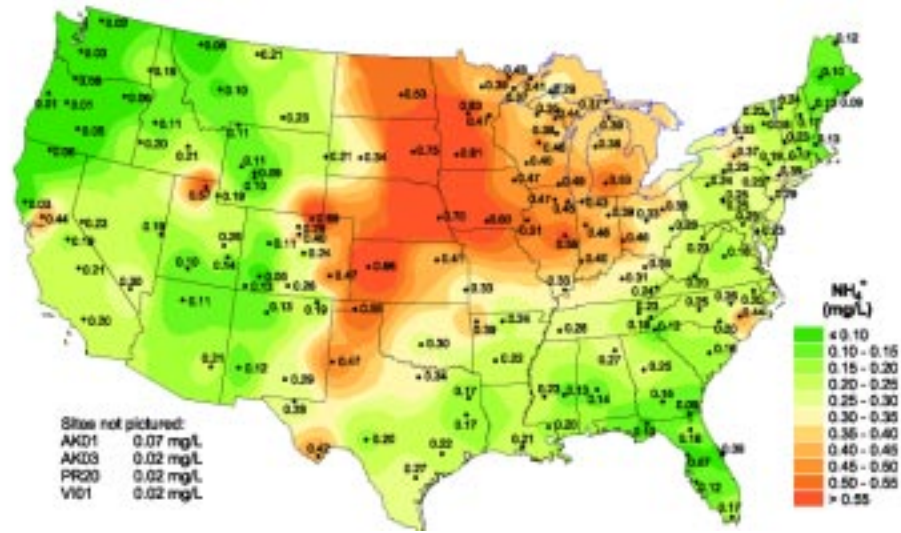


Figure 3. Ammonium ion concentration in precipitation for 1998. National Atmospheric Deposition Program/National Trends Network¹²

A modified Seasonal Kendall analysis of trends in ammonium in precipitation is shown in Figure 4. The effect of trends in precipitation volume was removed prior to the non-parametric test for trends in ammonium concentration. Approximately 23% of the sites had statistically significant ($\alpha < 0.05/n$) increasing trends, mostly in the Southeast and West. Decreasing trends were observed at less than 1% of the sites.



Figure 4. Trends in ammonium concentration in precipitation for the period 1981-1997. (USGS, Mark Nilles, private communication)

¹² NADP/NTN (<http://nadp.sws.uiuc.edu>)

MEASUREMENT

The accurate quantification of atmospheric ammonia is particularly challenging, primarily for two reasons. Firstly, ammonia is a sticky gas that readily adsorbs onto almost all surfaces. Much of the adsorbed material will subsequently desorb if ammonia levels decrease in the sample air stream. Thus, contact surfaces in inlets, samplers, and analytical systems can cause both positive and negative artifacts in the measurement of ammonia. Secondly, the human body produces its own ammonia emissions, which provides an opportunity for measurement/sample contamination.

A variety of techniques have been used to measure ambient ammonia. Integrated samples have been collected with passive samplers, sulfuric acid bubblers and citric acid coated filters and denuders. Chemiluminescence NO_x monitors will respond to ammonia when a molybdenum catalyst in the inlet is operated at high temperature. Ambient ammonia concentration can then be determined by differencing scrubbed and unscrubbed sampling streams.

Two promising new techniques for the measurement of ambient ammonia are currently being evaluated. NOAA has developed a chemical ionization mass spectrometer (CIMS) that can measure sub-parts-per-billion levels with a one-second response time. NOAA has just completed an extensive comparison of their CIMS instrument with a citric acid denuder system. These two techniques agreed very well. EPA is investigating the use of ion mobility spectroscopy (IMS) for ammonia measurement. Ammonia's strong proton affinity makes it a good candidate for IMS. The IMS can sample at one-second intervals and is a good candidate for on-road measurements.

Historically, the primary methods available for determining emissions from large area sources were point-sampling techniques employing flux chambers or evacuated canisters followed by analysis of the appropriate gas samples. Remote sensing techniques are now available for quantifying emissions from large, heterogeneous area sources, such as municipal wastewater treatment facilities, waste lagoons, and surface coal mines. These techniques produce a path-integrated concentration, typically reported in units of parts per million-meter (ppm-m) of the species of interest, eliminating concern over source heterogeneity. Open-path Fourier transform infrared (OP/FTIR) spectroscopy is one of the remote sensing techniques that has received wide attention within the last decade.

The measurement of the ammonium content of ambient aerosols has traditionally utilized integrated filter collection followed by laboratory analysis of the filter extract. In recent years, new techniques have been developed for the semi-continuous (5-15 min) speciation (including ammonium) of bulk atmospheric aerosols. A comparison of several of these techniques was conducted as part of the recent Atlanta PM "SuperSite" study with encouraging results (Figure 5)¹³.

¹³ Rodney Weber, Georgia Institute of Technology, private communication.

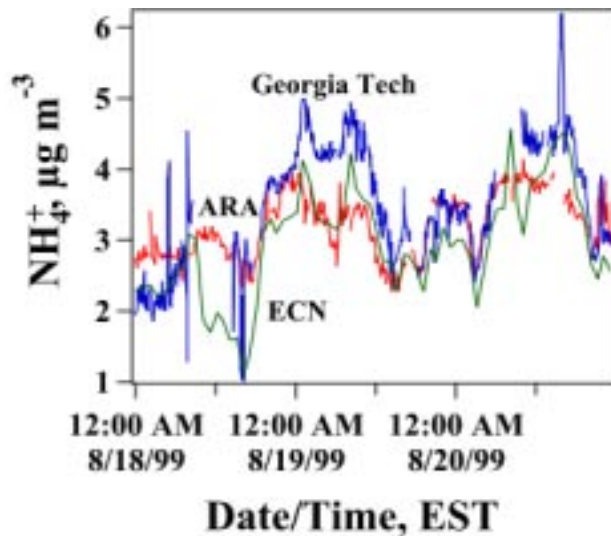


Figure 5. Aerosol ammonium time series from three semi-continuous aerosol speciation monitors. Data collected in Atlanta during the 1999 PM “SuperSite” experiment. ARA (Atmospheric Research Associates), ECN (Netherlands Energy Research Foundation)

In addition, several single-particle mass spectrometer systems are now operational that are capable of characterizing the composition of individual particles. These fast-response aerosol speciation systems are revolutionizing the measurement of particle-phase ammonium, and promise to provide insights into the chemistry of atmospheric ammonia/ammonium and source/receptor relationships that were not previously possible.

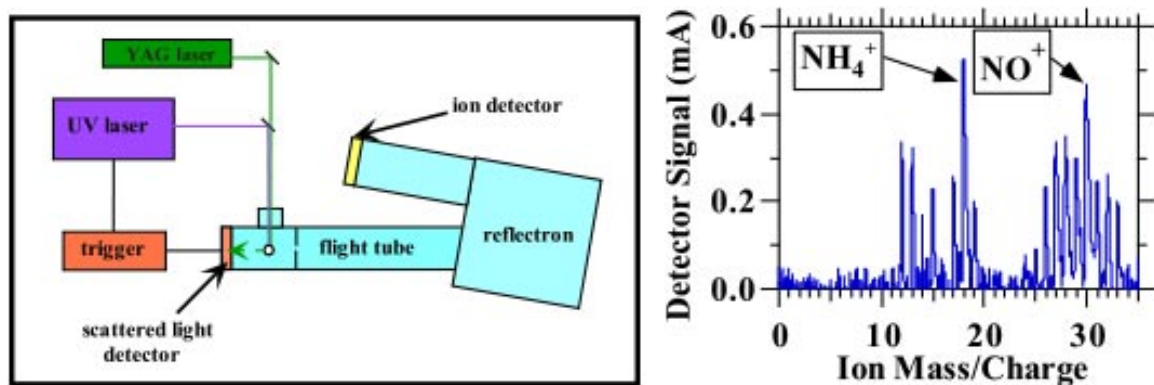


Figure 6. NOAA’s Particle Analysis by Laser Mass Spectrometer (PALMS) single particle mass spectrometer with a mass spectra of a ammonium particle.

Precipitation chemistry samples are integrated over a two-week period at the vast majority of NADP/NTN sites. A limited number of the Atmospheric Integrated Research Monitoring Network (AIRMoN) sites (part of NADP/NTN) perform event sampling. The ammonium concentrations in samples from the former sites can be compromised by biological activity in the sample containers. This effect is significantly reduced at the

event sites, since the samples spend a shorter time in the field containers and the samples are either refrigerated or preservatives are added to minimize biological activity.

RESEARCH NEEDS

This report provides a broad overview of what is known about atmospheric ammonia and its impact on local and regional air quality. Clearly, a great deal is already known and research programs are in place that promise a clearer understanding in the next few years. However, in an effort to insure that all the key information gaps are being addressed and that opportunities for interagency collaboration are identified, it is instructive to list the research needs that were identified by the Air Quality Research Subcommittee.

Emissions

The U.S ammonia emissions inventory is highly uncertain. An accurate assessment of emissions is the first step in the development of a successful management strategy. Therefore, improving the quality of the emissions inventory must be a high priority, with emphasis on the agricultural sector, which is clearly the largest contributor. Specifically, research is needed on:

- Emission factors for existing livestock operations.
- Impact of agricultural practices on ammonia mitigation.
- Ammonia emissions from light-duty vehicles as a function of operating condition and fuel type.
- Simultaneous on-road measurement of ammonia, NO_x, and CO emissions via remote sensing is recommended to determine the distribution and inter-relationship of emissions across individual vehicles and model years.
- Natural emissions.

Atmospheric Chemistry and Transport

Ammonia plays a key role in the formation and composition of fine particles, and the processes involved are not well understood. The ammonia/ammonium interchange has a significant impact on the distribution and deposition of ammonia and its conversion products. Specifically, research is needed on:

- The role of ammonia in particle nucleation.
- The interchange of ammonia/ammonium with vegetation, soils, and water bodies.
- The status of ammonium/sulfate neutralization, particularly in the eastern U.S., and the potential for ammonium nitrate formation.

Deposition

Ammonium is deposited as either gaseous ammonia, aerosol ammonium, or ammonium ion in cloud droplets and precipitation. The deposition of ammonium in precipitation is well characterized; less is known about the dry deposition of ammonia/ammonium.

Specifically, research is needed on:

- Deposition/emission of ammonia to/from a wide range of surfaces under different meteorological conditions.
- Deposition of aerosol ammonium. An improved quantification of aerosol ammonium deposition rates and distribution is needed.
- Source/receptor relationships, including apportionment of ambient ammonia and deposited ammonium to source categories and source regions.

Measurement

A wide variety of traditional and some exciting new techniques are being used to quantify gaseous ammonia and aerosol ammonium concentrations in the atmosphere. To date, only limited comparisons have been conducted. Specifically, research is needed on:

- New, fast response, and highly sensitive techniques for the measurement of ammonia/ammonium.
- Comparability of data from techniques being employed to measure ammonia/ammonium.
- Procedures to mitigate the impact of biological processes on the measurement of ammonium in precipitation.

Models

Computer models are important tools in the management of air quality. In this application, they are a bridge between science and policy and should represent the current state of knowledge. Many of the atmospheric processes critical to an accurate description of ammonia transformation, transport, and deposition are not adequately described in current air quality models. Specifically, research is needed on:

- Numerical methods that accurately characterize the formation of ammonium-containing aerosols, including their size distribution and optical properties.
- Model representations to account for the complex atmosphere/surface exchange processes involving ammonia.
- Evaluated buoyant plume rise schemes appropriate to the dispersion of ammonia from animal-rearing facilities.

APPENDIX A – MEETING AGENDA

CENR

AIR QUALITY RESEARCH SUBCOMMITTEE

October 15, 1999

AGENDA

Continuation of discussions on the integration of atmospheric and health-related research on PM

1:00 – 1:30

- Status of the PM research working group - Dan Albritton (NOAA)

Ammonia – emissions, transport, transformation fate and effects

1:30 – 2:15

- Overview of ammonia emissions from agricultural sources – Henry Tyrrell (USDA, CSREES)
- Nitrogen transport through a modern dairy production system - James Ferguson (Univ. of Pennsylvania)

2:15 – 2:35

- Ammonia “slip” – Thomas Feeley (DOE-FETC)

2:35 – 2:55

- Ammonia emission inventories – Jim Vickery (EPA)

2:55 – 3:15

- Ammonia transport, transformation, deposition, and measurement – Fred Fehsenfeld (NOAA)

3:15 – 3:45

- Ammonia deposition – Bruce Hicks (NOAA) and Mark Nilles (USGS)

General business

3:45 – 4:00

Dan Albritton will discuss future topics for the Subcommittee.

APPENDIX B – SELECTED REFERENCES

Langford, A.O., and F.C. Fehsenfeld, Natural vegetation as a source or sink for atmospheric ammonia: A case study, *Science*, 255, 581-583, 1992

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Kean, A.J., R.A. Harley, R.F. Sawyer, D. Littlejohn, D. Zucker, and G.R. Kendall, On-road measurement of ammonia and other motor vehicle exhaust emissions, to be presented at the 10th CRC On-Road Vehicle Emissions Workshop, San Diego, California, March 27-29, 2000.