

# US ANIMAL FEEDING OPERATIONS AIR EMISSIONS MITIGATION STATE OF SCIENCE

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*Abstract. Animal feeding operations present unique challenges to engineers and scientists seeking to develop suitable and effective mitigation strategies. This presentation addresses the current state of the science for abatement technologies used in the U.S. as well as available technologies not currently being implemented. The presentation will also discuss issues of practicality and economic feasibility that may currently be limiting the adoption of some mitigation approaches.*

*Keywords. Agriculture, Air Quality, Poultry, Manure Management, Treatment*

## INTRODUCTION

Animal Feeding Operations (AFOs), and especially Concentrated AFOs (CAFOs), can present unique challenges to the environment. AFOs have arisen owing to the economy of scale they can provide. Transportation, animal housing, feed, fuel, water and veterinary inputs can be managed at lower costs. Marketed product quality and quantity can be controlled for optimal profitability. Livestock and poultry manure management is part of the design of AFO systems, and the scale of these operations means that properly engineered treatment and storage systems are more likely to be employed. However the scale of these systems also means that they can be significant sources of atmospheric and watershed contamination; and while agricultural water quality has been a focus for several decades, a focus on agricultural air quality is more recent.

The concentration of animal units, whether on a farm, a locale, or a region, can present substantial environmental challenge. However, this concentration of animal units is also an opportunity for large-scale and efficient management and mitigation of environmental impacts. Despite this opportunity, air quality and water quality together represent the substantial majority of complaints and regulatory challenges to AFOs. Research and development to mitigate the impact of AFOs on agricultural air quality in the U.S. has increased greatly in recent years, in part due to increased regulatory scrutiny of AFOs, litigation regarding public nuisance and interpretation of applicability of community right-to-know laws and an increase in funding under the USDA National Research Initiative's Agricultural Air Quality Program (and previously, under the USDA Initiative for the Future of Agricultural and Food Systems). Implementing best management practices (BMPs), and developing new BMPs and best-available technologies, has been a focus for the USDA NRCS under the Conservation Innovation Grants and EQIP programs and many Land-Grant University projects. Funding has been applied to the broad arena of agricultural air quality, i.e. cropping systems, tillage, forestry and AFOs. With the recent acceleration in efforts to address air quality and mitigation of US AFOs, it is appropriate to examine the current state of the science.

## STATE OF THE SCIENCE – US AFOs

What is the current state of the science with respect to mitigating US AFO air emissions? A review of recent and current funded air quality projects (USDA, 2008) and recent air quality conferences shows a wealth of new material and accelerated activities. Broadly speaking, the following list of focus areas can be noted:

- Baseline emissions quantification, including improved measurement systems and sampling protocols.
- Model development and validation.
- Mitigation efforts.

## BASELINE EMISSIONS QUANTIFICATION

### *Recent baseline emission data*

A wealth of recently completed and current projects is becoming published in the scientific literature. Topical areas include: particulate matter properties, emissions, and composition; gaseous emissions including ammonia as a particulate pre-cursor, carbon dioxide, methane, hydrogen sulfide, volatile organic compounds, sulfur oxides and nitrous oxide; odor properties, composition, and emissions. Specialty conferences, technical committees, multi-state Hatch projects and other research groups are collecting and publishing this information.

By way of example, Tables 1 and 2 list recently acquired ammonia emission data for US broiler chicken housing (from Burns et al 2007a, Table 1) and a comparison to European literature (from Wheeler et al., 2006). By contrast, six years ago there were no

published US ammonia emissions data. Comparison of US baseline data to European data show generally lower values in the latter owing to new litter after each flock, smaller mature bird weights, and bird age at emissions sampling. The earlier literature also lacked any statement of uncertainty in measurements and details regarding production practices in the houses that were sampled. This is a common difficulty in assessing much of the recent literature on baseline emissions.

**Table 1. Comparison of ammonia emission rates (ER, g/bird-d) of the commercial broiler houses among various U.S. studies**

Reference	Growth Period, d	Stocking Density, (birds m <sup>-2</sup> )	Flocks	Litter	Mean ER, g/bird-d	Location
Burns et al. (2007b)	52	12.7	3	New	0.49	Kentucky, U.S.A
Burns et al. (2007b)	52	12.2	9	Built-up	0.62	
Wheeler et al. (2006b)	42	14.7	10	New	0.47	Kentucky and Pennsylvania U.S.A
	42	14.7	12	Built-up	0.65	
	49	13.4	24	Built-up	0.76	
Burns et al. (2003)	63	10.8	20	Built-up	0.98	Tennessee, U.S.A
	42	16.1	9	Built-up	0.92	
Lacey et al. (2003)	49	13.5	12	Built-up	0.63	Texas, U.S.A
Seifert et al. (2004)	42	20	1	Built-up	1.18	Delaware, U.S.A

**Table 2. European ammonia emission rates for broiler housing (from Wheeler et al. 2006)**

Reference	Market Age	Stocking Density (birds m <sup>-2</sup> )	Litter*	Mean ER g/bird-d
Müller (2003) German/Czech	32	n/a	New?	0.09
Demmers (1999) United Kingdom	32	25	New	0.11
Wathes (1997) United Kingdom	32	9.3 W 9.4 Su	New?	0.26
United Kingdom			New?	0.48
The Netherlands			New?	0.27
Denmark			New?	0.21
Germany			New?	0.44

### **Measurement systems and sampling protocols**

Most housing emissions studies in the U.S. have recently settled upon a fairly standard set of equipment and protocols. This has arisen in part from Air Quality Consent Agreement between the USEPA and livestock and poultry groups. Researchers involved in these and related studies have developed a consistent set of techniques for most emitted constituents of interest (Burns et al., 2006, 2007c; Moody et al., 2006), and for the accurate determination of ventilation rates from buildings (Gates et al., 2004). However, the current approach relies on a reduced sample of sites (e.g. three broiler houses in the entire U.S.) and a high frequency emissions rate sampling strategy. This needs to be re-evaluated as baseline values are published.

While substantial recent progress is noted in determining baseline emissions for various US AFOs, there remain substantial unknowns. Since published baseline emissions are used as representative sources for design, for modeling and for regulation, the variability in baseline emissions, and more importantly the underlying factors which are responsible for this variability, need to be better understood and documented. Always, the measured variability should be reported.

For example, for the broiler emissions cited above, there is a strong linear correlation between daily emissions and bird age; the single average emission values per study in Tables 1 and 2 (expressed on a per bird per day basis) miss completely this key factor. Burns et al (2007a) noted that emissions factors reported for broilers can be misleading, depending on market age, bird age when emissions were measured, and whether new litter was used. They reported (mean  $\pm$  std. dev.) emissions of  $12.4 \pm 9.4$  kg/d-house (new litter flocks), compared to  $14.6 \pm 9.0$  kg/d-house (built-up litter flocks).

A useful and cost-effective approach to sampling protocols utilizing less expensive monitoring equipment and more frequent, random visits to measure emissions has been developed in Europe (Mosquera-Lousada and Ogink, 2006; Vranken et al., 2004). This better captures variability within a farm over seasons and animal size, between farms on a similar day, and between farms over seasons. This sampling protocol is now the basis for performance evaluation of Dutch air mitigation systems. The use of less expensive monitoring equipment (Gates et al., 2005) and a larger sample of houses was the strategy employed in the US baseline ammonia emissions studies documented by Wheeler et al. (2006) and Liang et al., (2005, 2006). A comparison between this and the more sophisticated system appears quite favorable (Amaral et al., 2007).

### ***The importance of documenting emissions variability***

A need to quantify variability in emissions estimates has been noted by some researchers, e.g. Burns et al. (2007a), Mosquera-Lousada and Ogink (2006), Gates et al., (2008). Why is documenting the variability of housing emissions important? Frankly, without an understanding of the range in expected emissions profiles it is unlikely that reasonable mitigation technologies can be designed to fit an operation.

Consider a technology to scrub ammonia from building ventilation air. To design the scrubber system, one must determine typical, minimum and maximum design ventilation rates that will reasonably be expected to require treatment, and the typical air stream concentrations of ammonia at these design ventilation rates. If recently acquired emissions data are presented solely in terms of daily emissions rates per animal mass, then a designer will be forced to make some critical assumptions regarding air stream ammonia concentration, ventilation rate and their variability with bird age. This is despite the fact that this information has been collected as part of the emissions sampling!

Such an approach to design is a recipe for failure. The design failure could occur because the system was under-sized and did not perform to a minimum performance standard (which does not currently exist in the U.S.); or it could as readily be expected to fail because while it performs flawlessly, its construction cost and operating costs cannot be supported under the income stream generated by the AFO.

Proper engineering design of abatement technologies starts with a reduction in the number of critical assumptions made owing to a lack of pertinent data in the scientific literature.

## **MODEL DEVELOPMENT AND VALIDATION**

Models have a key role to play in both developing mitigation technologies (e.g. unit operations and transport phenomena) and in assessing fate and downwind transport on local, regional, national and global scales. Model efforts for improving abatement technology designs are also a critical and evolving area.

Modeling research includes: local air dispersion modeling, local and regional impacts, permitting, emissions inventory models, and process-based modeling to enhance understanding of underlying phenomena and potential for mitigation. Properly developed and validated models are critical. Use of emissions measurement literature to develop, calibrate and validate such models requires appropriate documentation of the monitoring protocols, animal housing system, animal management issues including feed regimes, stocking density and weight, season, etc.

The range in measured variables, or some other means of expressing measurement uncertainty, is also critical for model input/output sensitivity. A simple example of the utilization of documented measurement uncertainty, coupled with features unique to broiler rearing, is in Gates et al. (2008), in which baseline emission results from Wheeler et al. (2006) were utilized to construct an ammonia emissions inventory that could be compared to USEPA estimates. Because Wheeler et al. (2006) provided estimates of uncertainty in their published baseline emissions, the inventory model was developed to predict emission inventory estimates and a measure of uncertainty in these estimates stated with an appropriate measure of statistical confidence.

### ***Modeling for mitigation design strategies***

Models are a key part of engineering design. A rich engineering literature exists for air treatment technologies; many developed and applied for decades in the chemical engineering journals. Air emissions mitigation can be accomplished by strictly chemical means (e.g. an acid scrubber for removal of ammonia), or by biochemical means (e.g. use of nitrifying bacteria to consume

ammonia in a gas-phase biofilter). This latter technique has substantial prior research in wastewater treatment systems. Hence, model development for bio-based mitigation design strategies will emerge to provide a better understanding of design trade-offs. An example of a relevant, current model for gas-phase biofiltration for ammonia removal is presented by Baquerizo et al (2007). Further refinement, and development with an objective of model use for engineering design, remains as a significant barrier.

### ***Modeling for fate and transport***

Perhaps the most useful short-term application of models for fate and transport is for local dispersion of odors. Because odor complaints are a leading public nuisance issue (whether regulated *per se* or not), the fate of odors downwind of an AFO is of considerable importance and has been the focus of substantial US research and development for more than a decade.

Odor source variability includes some of the same issues as for gaseous emission variability, and odor dispersion models have substantial uncertainty. For example, a recent study by Henry et al. (2007) showed an excellent average relationship between predicted and measured odor concentrations but substantial range, with 64% of measurements falling within the range of predicted values. Despite such large uncertainty, odor dispersion modeling will be a critical facet for facilities siting, mitigation assessment, and related local regulatory issues.

A good example of odor model use for local transport is presented by Jacobson et al. (2005) and Guo et al. (2005), in which a science-based dispersion model for setback distances from AFOs was developed and assessed, using “annoyance curves”. Substantial variability was observed for measured odor intensities and model predictions need further improvement; however this sort of approach is likely to be a critical component for assessing the performance of emissions mitigation technologies.

Regional and larger scale modeling is of particular interest for understanding the dynamics of fate and transport. It is also beyond the scope of farm-level air emission mitigation assessment, although of course there is a direct linkage between on-farm emissions and their contribution to larger-scale environment impacts.

## **MITIGATION EFFORTS**

European research over the past two decades has advanced significantly, especially with regard to baseline quantification, measurement systems and protocols, and mitigation technologies for ventilation air. In part this is because of a different regulatory structure, with an emphasis on ammonia emission reduction and stringent permitting procedures for new facilities and renovations. The next speaker will elaborate on European progress.

Results from recent US baseline emissions quantification from AFOs have tended to be similar to that reported in the European literature; however this was not expected given the substantial differences in housing, feeding management and ventilation systems employed.

Numerous air emissions mitigation efforts have been studied in recent years in the U.S. These efforts include: dietary manipulation, feedlot and building dust control, management of housing, manure and ventilation, ventilation air dispersion techniques, manure and litter amendments, and treatment systems for housing and waste storage ventilation airstreams.

### ***Opportunities for Mitigation***

Efforts to mitigate emissions from AFOs can be divided into pre- and post-generation. In principle, methods to reduce the potential for emissions are attractive since they can also improve the economics and consequently create an added incentive for rapid adoption by industry.

#### **Feed supplements and Dietary Manipulation**

Dietary manipulation is a key example of a pre-generation mitigation opportunity. Animals are fed nitrogen in the form of crude protein, and if key amino acids are supplemented to better match biological function at different phases of growth, the crude protein is used more efficiently. Often, the resultant diet is more cost-effective than typical diets, and this cost-savings will continue to accelerate as use of crystalline essential amino acids becomes more prevalent and less expensive. Better matching feed ration to animal requirements results in less nitrogen loss to the feces, reduced potential for ammonia formation (Ferguson et al. 1998a,b), and has been shown to be a viable means of ammonia reduction on a commercial scale (Liang et al., 2005, 2008).

Additionally, substantial research on various feed supplements targeted toward improved feed conversion efficiency has been performed over the past two decades. Strategies to enhance gut flora with “enzyme cocktails”, improve phosphorus uptake efficiency by feeding phytase, and use of various plant extracts to alter feces composition and subsequent breakdown are widely reported in the literature. Certain of these strategies have been widely adopted, for example the mandatory use of phytase in broiler diets on the Delmarva Peninsula, while others appear to have more limited adoption.

#### **Facilities Design:**

Another opportunity for air emissions mitigation includes facilities design. This is not strictly a “pre-generation” opportunity, but if key elements are included in the design of facilities, they effectively stop or reduce emissions prior to production. Key examples include:

Separate feces from animals and their housing: manure belts in egg layer housing are one example of a technology that is rapidly gaining favor. Belts allow rapid drying of feces which in turn suspends microbial activity, and removal of feces to a storage area that does not need ventilation at the rate that a production house requires for laying hen comfort. Remove urine from feces and transport either or both out of the livestock area. Opportunities include new floor designs that actively shunt urine away from feces.

Solid-liquid separation to take advantage of existing waste-water treatment technologies. This technology is mature, and collection of manure for example in shallow that are flushed regularly, rather than in deeper pits that serve as storage, can reduce housing emissions.

Energy-efficient building ventilations system designs: there is no substitution for proper quantities of fresh air, delivered to the animals, in modern facilities. The fundamental trade-off however between the need to temper fresh air for some species (e.g. poultry and swine) and the energy cost of this tempering, is a leading cause of ventilation reductions which in turn spawn a host of problems including poor indoor air quality. Technologies to improve energy efficiency, such as use of attic tempering for ventilation air in broiler chickens, biomass gasification to provide supplemental heat, and use of compact fluorescent lighting to reduce electrical load are examples that are not generally recognized as directly relating to air emissions mitigation. Outreach and education, as well further research and development, are clearly needed to change perceptions on the importance of ventilations system design and operation to control air emissions.

Physical barriers to odor and gas transport, such as waste storage pond covers, and active capture and treatment of methane digester headspace emissions.

Note that these mitigation strategies must be part of a whole system approach, i.e. mitigating housing emissions by means of moving manure out of the facility means that the manure storage facility design is also important. Further, regardless of design feasibility, proper management is critical. There is tremendous opportunity to improve both design and facilities management by a closer coupling between design engineers and producers. Opportunities for technical service providers to provide this coupling are currently limited owing to the lack of economic incentives for either party.

### ***Post-generation technologies***

Post-generation technologies include a broad array of activities, including feedlot and building dust control, management of housing, manure and ventilation, ventilation air dispersion techniques, manure and litter amendments, and treatment systems for housing and waste storage ventilation airstreams. Some of these are briefly reviewed below.

#### **Room air treatment**

Room air treatment technologies that have been tried but have not been successful include dust control with oil spraying (effective, but messy), ozonation (Elenbaas-Thomas et al., 2005) and odorant masking.

#### **Ventilation air treatment**

Ventilation air treatment technologies include ozonation and odorant masking, neither of which has proven to very effective. Other more promising technologies include means for dust and gaseous emissions reduction. One simple technique that is becoming better understood is use of windbreak walls downstream of exhaust ventilation fans. The walls can be a combination of physical barriers to divert exhaust air (Figure 1), vegetative buffers to physically capture dust from the exhaust air, or vertical chimneys for improved dispersion. These techniques rely primarily on physical treatment to remove dust, which in turn reduces odor and certain gas emissions; or improved physical dispersion which acts to improve downwind odor concentrations but does not treat the ventilation air.



**Figure 1: A simple physical barrier around exhaust ventilation fans to reduce dust emissions.**

Active treatment of AFO ventilation air for odor or gaseous emission controls are emerging in the US. These include scrubbers, for example, acid scrubber for ammonia removal (Manuzon et al., 2007); and gas-phase or trickling biofilters for ammonia and/or odor mitigation (Baquerizo et al. 2007; Maia et al., 2006; Nicolai et al., 2006; Devanny et al., 1999; Zhang, 2005). Design criteria, and practical engineering details including ways to bring ventilation air to a piece of treatment equipment, are generally lacking and seen as substantial hurdles to current adoption. Their inclusion in new facilities is more likely in the shorter term.

Aerobic biofilters are gas-phase heterogeneous reactors which convert contaminants into CO<sub>2</sub>, water vapor and organic biomass (Devanny et al., 1999). Biofiltration uses different processes to remove pollutants in the air stream including biodegradation, adsorption, desorption and absorption. The liquid phase in a biofilter is stationary where microorganisms organize themselves as a biofilm on the surface of the medium or are suspended into the water phase close to the medium to convert organic matter into more stable and biodegradable forms.

A concern with gas-phase biofilters is that incomplete denitrification may result in elevated production of N<sub>2</sub>O, a problem not as likely to be encountered in trickling film biofilters such as in waste-water treatment facilities. Since N<sub>2</sub>O is a strong greenhouse gas, its generation during the breakdown of ammonia would be an unwelcome side effect. An example gas-phase biofilter system being tested for waste storage headspace gas treatment is illustrated in Figures 2 and 3 (Maia et al., 2006). Regardless, gas-phase biofilters show great promise to handle particulate matter loading and to mitigate both odors and gaseous emissions.

Several challenges exist when devising new strategies to handle ventilation air.

- First, the sheer volume of air that is utilized to maintain temperature and humidity within facilities can be a significant obstacle for engineers trained in “stack” industry abatement technologies. It is suggested that substantial treatment of some ventilation air, especially for odor abatement, may be more practical than complete treatment of all air.
- Second, ventilation air is generally contaminated with substantial particulate matter that can rapidly degrade scrubber or biofilter performance if not treated (see Figure 4).
- Third, these volumes of ventilation air are provided by propeller fans that often have marginal performance curves and so the addition of any significant downstream treatment which includes additional pressure drop will require fan replacement, consume greater energy per unit volume of air moved, and require facilities re-design (or remodeling) to capture and treat this airflow (see examples in Figure 5).
- Fourth, many facilities (e.g. dairy free-stall barns, turkey growout barns) rely on natural ventilation, making treatment impossible.



Figure 2: Gas-phase biofilter to treat headspace gases for odor and ammonia.



**Figure 3: Treatment of headspace gases in waste storage structures involves minimum ventilation for maintaining methane concentration below explosive limits and hydrogen sulfide below dangerous limits, and downstream treatment of the exhaust with gas-phase biofiltration for odor and ammonia removal (see Figure 2). Background: the swine facility utilizes exhaust stacks for high velocity ejection of ventilation air, pull-plug gravity flow systems for manure handling, collection into an in-ground tank (concrete pad in middle-ground), and storage in two above-ground impermeable tanks for twice-annual pumping to direct injection sites for crop fertilizer.**

### Manure and Litter Amendments

This encompasses a variety of techniques including physical drying and separate storage of feces, acid-based amendments to control pH of litter, bedding or manure pack and thereby reduce ammonia volatilization, and application of urease inhibitors to stop the breakdown of uric acid. Each has clear potential under certain applications. Each presents management challenges. Most need additional investigation of economic trade-offs.

Examples include:

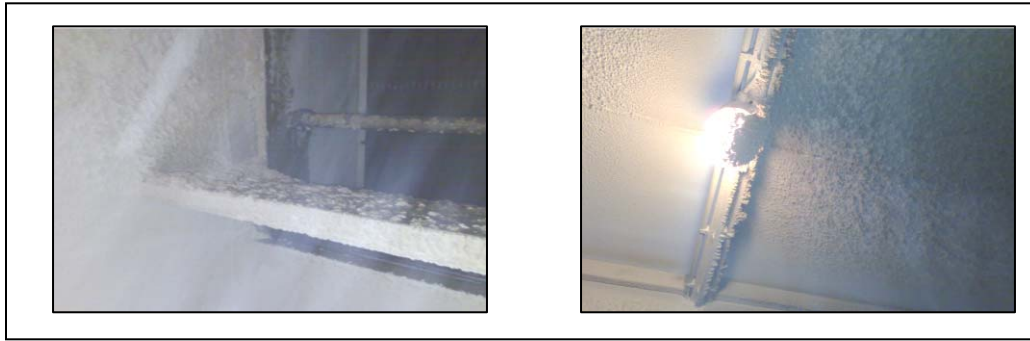
- Use of broiler litter amendments to reduce ammonia volatilization in housing are often coupled with reduced minimum ventilation settings that provide poor control of litter moisture. As the effect of the amendment wears off (after about 3 weeks or less) the litter is wet and ammonia concentrations in these houses can rise above those that were ventilated to recommended rates and did not use litter amendment (Casey et al., 2005).
- Urease inhibitors can be used to stop the enzymatic activity that breaks down uric acid and creates ammonia (Singh et al., 2005). Commercially available inhibitors in the US tend to be most effective on materials at higher moisture content, although work on beef cattle feedlots (Parker et al., 2004; Shi et al., 2001) and broiler litter (Singh et al., 2005) have shown limited success. Recent German studies have involved proprietary inhibitors that appear to work at lower media moisture contents (Hartung, E. personal communications, June 2006).
- Alum and other acid-based amendments to layer feces in high rise layer housing. Problems with liquid alum application are primarily related to its caustic action on building materials.

### Other Opportunities

A likely increase in on-farm biogas production is expected as energy costs continue to increase and more uniform acceptance of on-site electricity generation occurs. With increased incidence of captured slurry under cover, there will be a reduction in fugitive odor emissions and in baseline gaseous emissions from a facility. By moving the waste from a building, ventilation requirements during cold weather (for indoor air quality) are greatly diminished. Treating a relatively low volume of methane digester headspace gas may be more economically viable.

An economic incentive for adoption of air emission mitigation technologies may be realized as carbon credit trading is further developed in the US. Regular payments for utilizing a mitigation technique could be a key factor for adoption.

A need for increased energy efficiency in confinement AFOs will likely cause a renewed focus on improved facilities and ventilation system engineering. As existing facilities age, their replacement with newer designs will afford an opportunity for abatement technologies to be designed “from the ground up”.



**Figure 4: Dust in ventilation exhaust air remains a substantial challenge to mitigation technologies. Seen in these photos is dust accumulation in a broiler house upstream of a scrubber/biofilter assembly. Substantial dust clogging impairs scrubber operation and creates a maintenance headache.**



**Figure 5: Treating ventilation air from AFO structures involves substantial facilities engineering and increased energy costs for even the simplest of AFOs. Top: two open air, horizontal biofilters for treating swine barn ventilation air. Center: a swine barn ventilation system being prepared for downstream mitigation. Bottom: a swine barn (left) and broiler barn (right) with ventilation air treatment systems. Summary**

## SUMMARY

The state of the science for US Animal Feeding Operations emissions mitigations is maturing. Specific mitigation techniques are needed to control gaseous and odor emissions in an efficient and cost-effective manner. There is currently no consistent federal policy nor regulation regarding air emission mitigation strategies, although there is substantial development of best management practices and best available technologies that have been, and continue to be developed. The current regulatory environment does

little to encourage new mitigation approaches as part of best management practices; litigation often drives adoption of a best available technology among a limited selection of choices with unclear economic and technical feasibility.

It is likely that a host of mitigation techniques will be needed to address continued air emissions concerns. Rather than looking for a single “silver bullet” solution a more reasonable approach is to select cost-effective combinations that match the economic, management and, perhaps regulatory constraints that vary regionally and by species. To accomplish this, a substantial effort is needed. While great progress has been made in some areas of AFO air emissions, substantial commercial-scale evaluation and validation is necessary.

The following comments are offered:

- Substantial work remains to develop and implement mitigation systems that are effective and cost-efficient.
- There is a lack of a cohesive national plan to develop abatement policies tied to performance criteria.
- Substantial recent progress has been made on US AFO emissions baseline estimates, but researchers and peer-reviewers must ensure that the inherent variability in these measurements is quantified and reported. Without this key understanding, process-based models that explore interactions among contributing factors cannot be properly validated, but they will be used as needed in the growing regulatory focus on AFO operation and especially in new facility permitting.
- There is tremendous opportunity to improve both mitigation design and facilities management by a closer coupling between design engineers and producers.
- Outreach and education, as well further research and development, are clearly needed to change perceptions on the importance of ventilations system design and operation to control air emissions.
- A useful and cost-effective approach to sampling protocols utilizing less expensive monitoring equipment and more frequent, random visits to measure emissions has been developed in Europe.
- Active treatment of AFO ventilation air for odor or gaseous emission controls are emerging in the US.
- The sheer volume of air that is utilized to maintain temperature and humidity within facilities can be a significant obstacle for engineers trained in “stack” industry abatement technologies. It is suggested that substantial treatment of some ventilation air, especially for odor abatement, may be more practical than complete treatment of all air.
- A concern with gas-phase biofilters is that incomplete denitrification may result in elevated production of N<sub>2</sub>O, a problem not as likely to be encountered in trickling film biofilters such as in waste-water treatment facilities.
- With increased incidence of captured slurry under cover, there will be a reduction in fugitive odor emissions and in baseline gaseous emissions from a facility.
- Regular carbon credit payments for utilizing a mitigation technique could be a key factor for adoption.
- As existing facilities age, their replacement with newer designs will afford an opportunity for abatement technologies to be designed “from the ground up”

## REFERENCES

- Amaral, M.F.P., R.S. Gates, E.G. Wilkerson, D.G. Overhults, I.F.F. Tinôco, H. Li, R.T. Burns, H. Xin and J.W. Earnest. 2007. Comparison between two systems for ammonia emission monitoring in broiler houses. Proceedings of the International Symposium on Air Quality and Waste Management for Agriculture, 15-19 September. St. Joseph, MI.: ASABE:
- Baquerizo, G., X. Gamisansa, D. Gabriel and J. Lafuente. 2007. A dynamic model for ammonia abatement by gas-phase biofiltration including pH and leachate modeling. *Biosystems Engineering* 97:431-440.
- Burns, R.T., K. A. Armstrong, F. R. Walker, C. J. Richards, and D.R. Raman. 2003. Ammonia emissions from a broiler production facility in the United States. In Proc. International Symposium on Gaseous and Odor Emissions from Animal Production Facilities, 88-95. Horsens, Denmark: CIGR.
- Burns, R.T., H. Xin, H. Li, S. Hoff, L. Moody, R. Gates, D. Overhults and J. Earnest. 2006. Monitoring system design for the southeastern broiler gaseous and particulate matter air emissions monitoring project. Proceedings of the Symposium on Air Quality Measurement Methods and Technology, 9-11 May, Durham NC. AWMA.

- Burns, R.T., H. Xin, R.S. Gates, H. Li, S. Hoff, L. Moody, D.G. Overhults and J.W. Earnest. 2007a. Tyson Broiler House Emissions Monitoring Project: Final Report. Available at: [www.abe.iastate.edu/wastemgmt/home.html](http://www.abe.iastate.edu/wastemgmt/home.html). Accessed 26 April, 2008.
- Burns, R.T., H. Xin, R.S. Gates, H. Li, D.G. Overhults, L. Moody and J.W. Earnest. 2007b. Ammonia emissions from poultry broiler systems in the southeastern United States. Proceedings of the International Symposium on Air Quality and Waste Management for Agriculture, 15-19 September. St. Joseph, MI: ASABE
- Burns, R.T., H. Xin, R.S. Gates, H. Li, L.B. Moody, D.G. Overhults, J. Earnest and S. Hoff. 2007c. Continuous monitoring method for ammonia emissions from poultry broiler houses in the United States. Page 152 in: Ammonia Conference Abstract Book, Monteny, G.-J., E. Hartung, M. van den Top and D. Starmans, editors. 18-21 March, Wageningen, The Netherlands. Wageningen Academic Publishers. 171 pp.
- Casey, K.D., R.S. Gates, A. Singh, A.J. Pescatore, E.F. Wheeler, H. Xin and Y. Liang. 2005. The effect of litter management on ammonia emissions from U.S. broiler chicken houses. Paper #615, Air and Waste Management Association 98th Annual Conference, Minneapolis, MN. June 21-24. AWMA
- Deviny, S. D., M. A. Deshusses, T. S. Webster. 1999. Biofiltration for Air Pollution Control. 1st ed., Boca Raton, Fla.: Lewis Publishers.
- Elenbaas-Thomas, A.M., L. Y. Zhao, Y. Hyun, X. Wang, B. Anderson, G. L. Riskowski, M. Ellis and A. J. Heber. Effects of room ozonation on air quality and pig performance 2005. *Trans. ASAE*, 48(3):1167-1173.
- Ferguson, N.S., R.S. Gates, J.L. Taraba, A.H. Cantor, A.J. Pescatore, M.J. Ford and D.J. Burnham. 1998a. The effect of dietary crude protein on growth, ammonia concentration and litter composition in broilers. *Poultry Science*. 77:1481-1487.
- Ferguson, N.S., R.S. Gates, J.L. Taraba, A.H. Cantor, A.J. Pescatore, M.L. Straw, M.J. Ford and D.J. Burnham. 1998b. The effect of dietary protein and phosphorus on ammonia concentration and litter composition in broilers. *Poultry Science*. 77:1085-1093.
- Gates, R.S., K.D. Casey, H. Xin, E.F. Wheeler and J.D. Simmons. 2004. Fan Assessment Numeration System (FANS) design and calibration specifications. *Trans. ASAE*, 47(5):1709-1715.
- Gates, R.S., H. Xin, Y. Liang, K.D. Casey and E.F. Wheeler. 2005. Method for measuring ammonia emissions from poultry houses. *J Appl Poult Res*. 14:622-634.
- Gates, R.S., K.D. Casey, E.F. Wheeler, H. Xin and A.J. Pescatore. 2008. U.S. broiler ammonia emissions inventory model. *Atmospheric Environment*. 42(14):3342-3350.
- Guo, H., L.D. Jacobson, D. R. Schmidt, R. E. Nicolai, J. Zhu, K.A. Janni. 2005. Development of the offset model for determination of odor-annoyance-free setback distances from animal production sites: Part II. Model development and evaluations. *Trans. ASAE*, 48(6): 2259-2268.
- Henry, C.G., S.J. Hoff, L.D. Jacobsen, D.D. Schulte, P.C. D'Abreton, R.J. Ormerod, G.G. Galvin and D.P. Billesbach. 2007. Downwind odor predictions from four swine finishing barns using CALPUFF. Proceedings of the International Symposium on Air Quality and Waste Management for Agriculture, 15-19 September. St. Joseph, MI: ASABE
- Jacobson, L.D., H. Guo, D. R. Schmidt, R. E. Nicolai, J. Zhu, K.A. Janni. 2005. Development of the offset model for determination of odor-annoyance-free setback distances from animal production sites: Part I. Review and experiment. *Trans. ASAE*, 48(6): 2259-2268.
- Lacey, R. E., J. S. Redwine, and C. B. Parnell, Jr. 2003. Particulate matter and ammonia emission factors for tunnel-ventilated broiler production houses in the southern U.S. *Trans. ASAE* 46(4): 1203-1214.
- Liang, Y., H. Xin, H. Li, R.S. Gates, E.F. Wheeler, K.D. Casey, B.R. Behrends and D.J. Burnham. 2008. Dietary manipulation to reduce ammonia emission from high-rise layer houses. Proceedings of the Conference on Mitigating Air Emissions from Animal Feeding Operations, 19-21 May. Ames, IA: Iowa State University Extension
- Liang, Y., H. Xin, H. Li, R.S. Gates, E.F. Wheeler and K.D. Casey. 2006. Effect of measurement interval on estimation of ammonia emission rates for layer houses. *Trans ASAE* 49(1): 183-186.
- Liang, Y., H. Xin, E.F. Wheeler, R.S. Gates, H. Li, J.S. Zajackowski, P. A. Topper, K.D. Casey, B.R. Behrends, D.J. Burnham and F.J. Zajackowski. 2005. Ammonia emissions from U.S. laying houses in Iowa and Pennsylvania. *Trans ASAE*. 48(5):1927-1941.
- Maia, G.D.N., R.S. Gates, E.G. Wilkerson, S.F. Higgins, A. Singh, J.L. Taraba. 2006. Characterization of headspace gases in ventilated and impermeable swine manure tanks and their abatement using biofiltration. ASABE Paper No. 064027, St. Joseph, MI: ASABE.
- Manuzon, R.B., L.Y. Zhao, H.M. Keener, M.J. Darr. 2007. A prototype acid spray scrubber for absorbing ammonia emissions from exhaust fans of animal buildings. *Trans. ASABE*, 50(4):1395-1407.

- Moody, L., H. Li, R. Burns, H. Xin and R. Gates. 2006. Quality Assurance Project Plan (QAPP) implementation for the southeastern broiler gaseous and particulate matter air emissions monitoring project. Presented at: Workshop on Agricultural Air Quality: State of the Science, Bolger Conference Center, Potomac MD. 5-8 June. ESA.
- Mosquera-Lousada, J. and N.W.M. Ogink. 2006. New measurement protocol for the determination of NH<sub>3</sub> emission factors from animal houses in the Netherlands. Proceedings of the Workshop on Agricultural Air Quality, 5-8 June. Available at: <http://www.ncsu.edu/airworkshop/>. Accessed 24 April 2008.
- Nicolai, R.E., C. J. Clanton, K. A. Janni and G. L. Malzer. 2006. Ammonia removal during biofiltration as affected by inlet air temperature and media moisture content. *Trans. ASABE*. Vol. 49(4): 1125-1138.
- Parker, D.B., M.B. Rhoades, Z.L. Perschbacher-Buser, and P. Sambana. 2005. Field evaluation of urease inhibitors for reduction of ammonia emissions from open-lot feedyards, In A&WMA's 98th Annual Conference & Exhibition-Exploring Innovative Solutions, Paper No. 1114: AWMA.
- Seifert, R. L., J. R. Scudlark, A. G. Potter, K. A. Simonsen and K. B. Savidge. 2004. Characterization of atmospheric ammonia emission from a commercial chicken house on the Delmarva Peninsula. *Environ. Sci. Tech.* 38(10): 2769:2778.
- Shi, Y., D.B. Parker, N.A. Cole, B.W. Auvermann, and J.E. Mehlhorn. 2001. Surface amendments to minimize ammonia emissions from beef cattle feedlots, *Transactions of ASAE* 44(3): 677-682.
- Singh, A., K.D. Casey, A.J. Pescatore and R.S. Gates. 2005. Efficacy of urease inhibitor to reduce ammonia emissions from broiler litter. Proceedings of the Animal Waste Management Symposium, Research Triangle Park, NC. Oct. 5-7. Page 18.
- USDA. 2008. Current Research Information System – NRI Air Quality. United States Department of Agriculture. Washington, D.C.: USDA. Available at: [www.csrees.usda.gov/fo/airqualitynri.cfm](http://www.csrees.usda.gov/fo/airqualitynri.cfm). Accessed 24 April 2008.
- Vranken, E. S. Claes, J. Hendriks, P. Darius and D. Berckmans. 2004. Intermittent measurements to determine ammonia emissions from livestock buildings. *Biosystems Engineering* 88, 351-358.
- Wheeler, E.F., K.D. Casey, R.S. Gates, H. Xin, J.L. Zajackowski, P.A. Topper, Y. Liang and A.J. Pescatore. 2006. Ammonia emissions from twelve U.S.A. broiler houses. *Trans. ASABE* 49(5):1495-1512.
- Zhang, Y. 2005. Indoor Air Quality Engineering. Boca Raton, Fla.: CRC Press LLC.