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Building Emissions Uncertainty Estimates

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Abstract
Analysis of the propagation of measurement error into a computed quantity such as building aerial emissions provides insight into which measurements are most critical and which would have the most impact on the computed quantity if improved. An analysis of different instrument measurements, sampling periods, and sites together comprise an objective means of determining optimal sampling strategies for measurements used to compute aerial emissions from livestock facilities. This article describes the uncertainty analysis for a measurement system used in emissions research, and how it can lead to improvements in measurement system design and implementation to obtain estimates of uncertainty in emissions. The system analyzed was used in a broiler house emission monitoring project that was part of the U.S. EPA Air Consent Agreement. The project required U.S. EPA category I Quality Assurance Project Plan (QAPP) Data Quality Objectives (DQO), which were developed from this uncertainty analysis. Results of the uncertainty analysis suggest that the combined standard uncertainty in ammonia emission from broiler houses in the study was typically less than 6%; it increased with uncertainty in ventilation rate, but decreased as ventilation rate and number of fans running increased. The combined standard uncertainty was quantified for normal measurement conditions (Case 1) and for conditions in which the instrumentation was at the calibration threshold (Case 2). A key conclusion was that, for the measurement system employed in this project, uncertainty in the measurements associated with ventilation rate are the major contributors to emissions rate uncertainty (ranging from 78% to 98.9% of combined standard emission uncertainty).

Keywords
Aerial emissions, Ammonia, Animal feeding operations, Component error analysis, Instrumentation

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BUILDING EMISSIONS UNCERTAINTY ESTIMATES

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ABSTRACT. *Analysis of the propagation of measurement error into a computed quantity such as building aerial emissions provides insight into which measurements are most critical and which would have the most impact on the computed quantity if improved. An analysis of different instrument measurements, sampling periods, and sites together comprise an objective means of determining optimal sampling strategies for measurements used to compute aerial emissions from livestock facilities. This article describes the uncertainty analysis for a measurement system used in emissions research, and how it can lead to improvements in measurement system design and implementation to obtain estimates of uncertainty in emissions. The system analyzed was used in a broiler house emission monitoring project that was part of the U.S. EPA Air Consent Agreement. The project required U.S. EPA category I Quality Assurance Project Plan (QAPP) Data Quality Objectives (DQO), which were developed from this uncertainty analysis. Results of the uncertainty analysis suggest that the combined standard uncertainty in ammonia emission from broiler houses in the study was typically less than 6%; it increased with uncertainty in ventilation rate, but decreased as ventilation rate and number of fans running increased. The combined standard uncertainty was quantified for normal measurement conditions (Case 1) and for conditions in which the instrumentation was at the calibration threshold (Case 2). A key conclusion was that, for the measurement system employed in this project, uncertainty in the measurements associated with ventilation rate are the major contributors to emissions rate uncertainty (ranging from 78% to 98.9% of combined standard emission uncertainty).*

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Gaseous and particulate matter emissions from poultry houses vary with season and weather patterns, management and feeding practices, housing styles, and other factors. Two high-quality data collection studies on ammonia emissions from poultry housing were recently completed in the U.S. The first study involved seven states, agencies, and associations and was funded under the USDA competitive grant program "Initiative for the Future of Agriculture and Food Systems" (IFAFS) to determine ammonia emission rates (ER) from poultry facilities (Gates et al., 2001). Twelve broiler houses in two geographical regions were monitored for more than one year (Liang et al., 2005; Wheeler et al., 2006). The second study involved ammonia emissions from two commercial broiler houses in Kentucky, as part of the U.S. Environmental Protection Agency's Air Consent Agreement (Burns et al., 2007a, 2007b). In this second study, continuous recordings of concentration and ventilation rate data were collected over a period of more than one year. This latter project is referred to as the "Kentucky Broiler Air Consent Agreement" or Kentucky Broiler ACA Project throughout this article. A set of Data Quality Objectives (DQOs) was developed to satisfy the requirements that the Kentucky Broiler ACA study comply with U.S. EPA Category I Quality Assurance Project Plan (QAPP). These DQOs were developed by analyzing how the key input measurements affect uncertainty in ER. The full Quality Assurance Project Plan (QAPP) has recently been published (Moody et al., 2008).

Estimates of building emissions from agricultural livestock and poultry operations should include a clear statement of uncertainty in published results (National Academy of Sciences, 2003), but often do not. An analysis of uncertainty in ER, as affected by measurements in primary variables such as constituent concentration and ventilation rate, is necessary to identify which measurement errors contribute the most to ER uncertainty. Some recent efforts to quantify uncertainty in air emissions research include Casey (2005) and Price and Lacey (2003). Casey (2005) established a methodology and provided specific uncertainty estimates for the U.S. IFAFS project, which forms the basis for this analysis. The objective of this article is to provide a similar, expanded uncertainty analysis for the ammonia emissions measurements made in the Kentucky Broiler ACA Project and make this available as a guide for future projects.

Definitions of accuracy, precision, bias, uncertainty, and error abound in the literature (e.g., Doeblin, 1990; Taylor and Kuyatt, 1994; ISO/IEC, 2008; NIST, 2009). Fundamentally, accuracy is how closely a measurement matches the "true" value (which may, or may not, be known). "Error" is considered a subjective term and is comprised in general of random and systematic components. The random component is the precision, and when quantified is called uncertainty. It represents repeatability in measurement. The systematic

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component may be removed by calibration, or accounted for using a component error analysis method as described in the next section, in which case it is also part of the overall uncertainty. The term "uncertainty" is used when one desires to ascribe a number to the estimate of error; thus, in general use the term "error" is qualitative and "uncertainty" is quantitative (ISO/IEC, 2008; Taylor and Kuyatt, 1994).

Component Error Analysis

A component error analysis can quantify the influence of measurement uncertainties on reported building emissions. Propagation of uncertainty from individual instrument measurements to a quantitative statement of uncertainty in building ER is performed by considering the contribution of each individual measurement's uncertainty, using a truncated first-order Taylor series approximation to ER (Doeblin, 1990; Taylor and Kuyatt, 1994; ISO/IEC, 2008; and Ku (1966) as cited in NIST, 2009). The measurement uncertainty in each component is propagated through the mathematical relation between measurements and ER (eq. 1). In principle, if all measurement inputs to the ER computation can be specified with a statistical basis for their uncertainties, then the resultant value of ER can be provided along with a combined statistical interpretation of its uncertainty. In this case, the resultant uncertainty in ER is referred to as the combined standard uncertainty. A statistical basis for the component inputs implies that it takes the form of a standard deviation; hence, these component uncertainties are called standard uncertainties to explicitly acknowledge that a statistical basis was used in their estimation. For further details, including methods for handling measurement uncertainty to obtain standard uncertainty, refer to Taylor and Kuyatt (1994), ISO/IEC (2008), and NIST (2009).

Simplified Equations from the USDA IFAFS Study

The component error analysis for the USDA IFAFS study was developed by Casey (2005) and is briefly summarized in this section. The building ER equation used was as follows:

$$\mathrm{ER} = Q_T \cdot C \cdot 10^{-6} \cdot \frac{T_{std}}{T_e} \cdot \frac{P_a}{P_{std}} \cdot \frac{w_m}{V_m} \qquad (1)$$

where

- ER = emission rate for the house (g h^{-1} $bldg^{-1}$)
- Q_T = total exhaust ventilation rate of the building at field temperature and barometric pressure (m^3 h^{-1} $bldg^{-1}$)
- C = gas concentration of the building exhaust ventilation air (ppm_v)
- w_m = molar weight of the gas (17.031 g $mole^{-1}$ for NH_3)
- V_m = molar volume of gas at standard temperature (0°C) and pressure (101.325 kPa) (0.022414 m^3 $mole^{-1}$)
- T_{std}, P_{std} = standard temperature (273.15 K) and pressure (101.325 kPa)
- T_e = absolute temperature of exhaust air (K)
- P_a = atmospheric barometric pressure at the monitoring site (kPa).

An estimate of variance for an ER, assuming independent input measures, is:

$$\Delta\mathrm{ER}^2 = \left(\frac{\partial \mathrm{ER}}{\partial C}\Delta C\right)^2 + \left(\frac{\partial \mathrm{ER}}{\partial Q_T}\Delta Q_T\right)^2 + \left(\frac{\partial \mathrm{ER}}{\partial T_e}\Delta T_e\right)^2 + \left(\frac{\partial \mathrm{ER}}{\partial P_a}\Delta P_a\right)^2 \qquad (2)$$

where

- ΔC = standard uncertainty in NH_3 concentration (ppm_v)
- ΔQ_T = standard uncertainty in building exhaust ventilation rate (m^3 h^{-1})
- ΔT_e = standard uncertainty in exhaust air temperature (°C)
- ΔP_a = standard uncertainty in barometric pressure, at location (kPa).

The square root of this expression, also termed the root mean square error, provides an estimate of uncertainty, expressed in physical units of ER. By taking the ratio of uncertainty in ER to the ER (ΔER/ER), relative uncertainty can be determined. This is a useful metric to assist in establishing DQOs for a study.

There are two classes of terms in each product on the right side of equation 2: the partial differentials of ER with respect to a primary measurement, and the uncertainty in that measurement (denoted by Δ). The partial differentials relate the physical relationships between measurements to the computed quantity. Uncertainty in each measurement (Δ value) is quantified as the component "standard" uncertainty, equivalent to a best estimate of component standard deviation (Taylor and Kuyatt, 1994). The uncertainty (ΔER) in computed ER is the combined standard uncertainty and can be used to make inferences such as confidence intervals for ER because it is a statistically derived quantity analogous to a standard deviation.

For total building ventilation rate, the partial differential $\partial\mathrm{ER}/\partial Q_T$ is based on individual measurements taken by the Fan Assessment Numeration System (FANS). These measurements are used to construct an individual *in situ* fan performance curve, thus requiring measurements of building static pressure (P_d), a regression slope (b) and intercept (a) that are unique to each operating fan in the building. Standard uncertainty in the building static pressure measurements is obtained from the sensor specifications, whereas for the slope and intercept parameters, the regression coefficient standard errors may be used as standard uncertainty. The concentration term in equation 2 is comprised of the standard uncertainty in the concentration measurement (typically based on linearity and precision of the measurement instrument) and the added uncertainty associated with the calibration gas used to conduct instrument calibrations. The last two terms on the right side of equation 2, corresponding to standard uncertainty in temperature and barometric pressure, are typically rather small compared to other terms and were neglected in this analysis. After dropping these two terms, equation 2 can be expanded to incorporate the contributions of the individual measurements (Casey, 2005). This equation forms the basis for the DQOs that were established for the Kentucky Broiler ACA Project:

$$\frac{\Delta ER}{ER} = \sqrt{\left(\frac{\Delta C}{C}\right)^2 + \left(\frac{\Delta Q'_T}{Q'_T}\right)^2} \quad (3)$$

where

Q'_T = standard moist air ventilation rate ($m^3\ h^{-1}$)

$$= Q_T\left(\frac{T_{std}}{T_e}\right)\cdot\left(\frac{P_a}{P_{std}}\right)$$

$\Delta Q'_T/Q'_T$ = uncertainty in standard moist air ventilation rate (adjusted for temperature and pressure).

Application to the Kentucky Broiler ACA Project

For the Kentucky Broiler ACA Project, ER was corrected for background ammonia concentration in the inlet. Thus, the following relationship for ER was used:

$$ER = Q_T\left(\frac{C}{T_e} - \frac{\nu_i}{\nu_e}\cdot\frac{C_i}{T_i}\right)\cdot 10^{-6}\cdot T_{std}\cdot\frac{P_a}{P_{std}}\cdot\frac{w_m}{V_m} \quad (4)$$

where

C_i = gas concentration of incoming (background) building ventilation air (ppm_v)

T_i = temperature of incoming air (°C)

ν_i, ν_e = specific volume of incoming and exhaust air, respectively, calculated from air temperature and RH (m^3 moist air kg^{-1} dry air).

The ratio of incoming to exhaust air specific volumes, ν_i/ν_e, is:

$$\frac{\nu_i}{\nu_e} = \frac{T_i(1+1.6078W_i)(1+W_e)}{T_e(1+1.6078W_e)(1+W_i)} \quad (5)$$

where the variable W is humidity ratio (kg water vapor kg^{-1} dry air; ASHRAE, 2009). Substitution into the equation for ER gives:

$$ER = Q_T\left\{C - C_i\frac{(1+1.6078W_i)(1+W_e)}{(1+1.6078W_e)(1+W_i)}\right\}\cdot 10^{-6}$$

$$\cdot\frac{T_{std}}{T_e}\cdot\frac{P_a}{P_{std}}\cdot\frac{w_m}{V_m} \quad (6)$$

An adjustment factor involving indoor and outdoor humidity ratio and related constants that is multiplied with inlet air concentration C_i in equation 6 can be computed for representative inside and outside moist air state points, as described below.

Methods

Representative Calculations to Define Measurement Quality Objectives

When designing studies under current EPA Category I QAPP requirements, measurement performance criteria are to be held to a stated level of uncertainty. Such a statement is called a Measurement Quality Objective (MQO) and serves as the basis by which future measurements should be taken to ensure controlled measurement uncertainty. To assess ER uncertainty in the Kentucky Broiler ACA Project, equation 3 was evaluated at representative values (and standard uncertainties) of NH_3 concentration and ventilation rate. All other constants and parameters used in this analysis are provided in table 1. It should be noted that the concentration measuring instrumentation used in the Kentucky Broiler Study had a reported linearity of 1% of reading and minimum detection level of 0.2 ppm for ammonia (Innova model 1412, LumaSense Technologies A/S, Ballerup, Denmark). Assuming this reported deviation from linearity is normally distributed, the minimum concentration measurement standard uncertainty is 0.5% (Taylor and Kuyatt, 1994; ISO/IEC, 2008; NIST, 2009). A 5% error on span check was used as the threshold to flag the need for recalibration.

Table 1. Parameters and constants used for uncertainty analysis.

Inputs	Value or Range	Measurement or Component Standard Uncertainty	
		Value	Notes
Concentration	0 to 100 ppm	RMS[a]	ppm
Calibration gas	100 ppm	3	% of span
Instrument	--	0.5 or 5	% of reading
Fan ventilation[b]			
Static pressure	17.5 Pa	0.0623 Pa	Constant
Fan curve: slope	-259 $m^3\ h^{-1}\ Pa^{-1}$	Varied[c]	% of value
Fan curve: intercept	38,216 $m^3\ h^{-1}$	Varied[c]	% of value
Building ventilation[c]	33,152 to 265,213 $m^3\ h^{-1}$	--	--
Number of fans	1 to 8	--	--
Barn air temperature	20°C	0.25°C	Constant
Barometric pressure	99.725 kPa	50.0 Pa	Constant
Constants			
NH_3 molar mass	17.031 g mol^{-1}		
NH_3 molar volume	0.02406 $m^3\ mol^{-1}$		
Standard pressure	101.325 kPa		
Standard temperature	293.15 K		
T_{std}/T_e	0.9318		
P_a/P_{std}	0.9842		

[a] RMS = root mean square calculation from measurement state point and standard uncertainties.
[b] These values for fan characteristics were used for all computations.
[c] Varied: 1%, 2.5%, 5%, 7.5%, 10%, or 25%.

A sensitivity analysis was performed using the component error analysis and ER given in equations 3 and 4, coupled with estimates of uncertainty for the equipment used in this study as listed in table 1. Two cases were evaluated to quantify ER uncertainty:

Case 1: Normal operation: Characterized by 0.5% standard uncertainty of instrument concentration measurement, 3% standard uncertainty on the gas calibration standard, and a range of 1% to 25% standard uncertainty in each fan's ventilation rate. Since building ventilation rate was comprised of multiple fans, we assumed that each fan's performance curve was identical and used a single slope and intercept (table 1). The range in fan ventilation standard uncertainties (1% to 25%) was generated by uncertainties in slope and intercept (1% to 25%) and static pressure measurement standard uncertainty (0.625 Pa).

Case 2: Worst-case operation: Similar to case 1 except that concentration measurement standard uncertainty was increased to the recalibration threshold of 5% of the reading.

Results and Discussion

Results of the analysis of these two cases are presented graphically in figure 1 and in table 2 for select state points. As building ventilation rate is increased by adding more fans, the combined standard uncertainty in ER drops to below 6% and 8% for Cases 1 and 2, respectively, for any fan ventilation rate uncertainty of 10% or less. At low ventilation rates, ventilation rate uncertainty has a pronounced effect on combined standard uncertainty. This ER uncertainty is positively related to ventilation rate uncertainty, with the maximum value of about 12% and 13% occurring when the ventilation uncertainty is 10% at low ventilation rates for Cases 1 and 2, respectively. During normal conditions of emissions monitoring (Case 1), the combined standard uncertainty in ER was less than 12% since the minimum ventilation rate of the houses monitored was approximately 39,000 m^3 h^{-1} (23,000 cfm) when fans were running, and was generally less than 6% for most operational states during the flock grow-out period. A reasonable estimate for standard uncertainty in ventilation rate for the case where each fan's

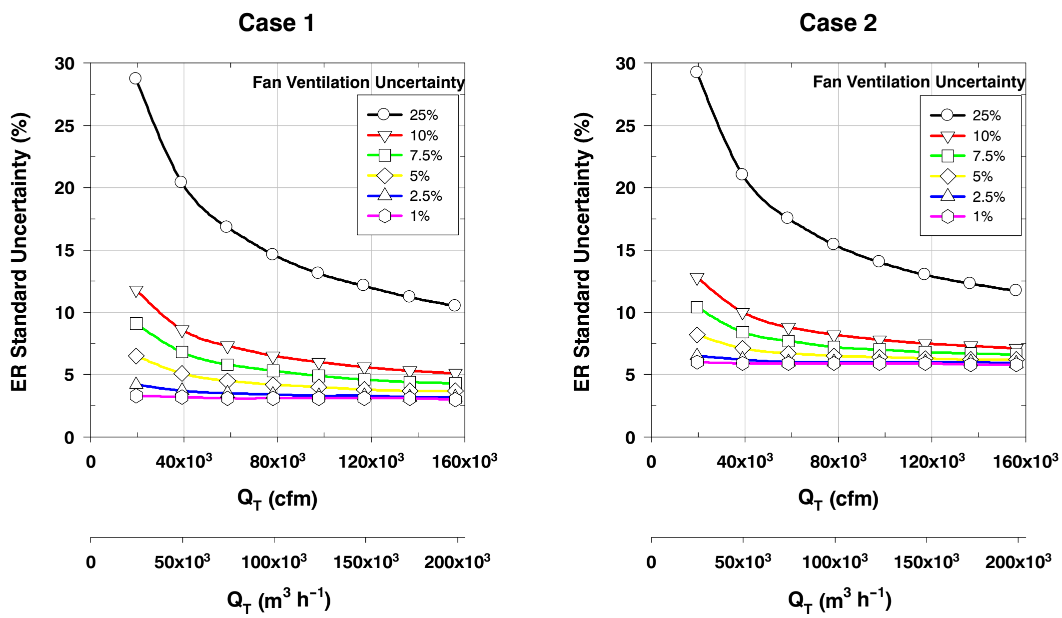

Figure 1. Combined standard uncertainty estimates for ER as function of building ventilation rate (*Q'*$_T$) and ventilation uncertainty. Note that each point along a curve represents one more fan with the same uncertainty being added. Case 1 uncertainties on inputs include 3% for calibration gas and 0.5% instrument standard uncertainty; whereas Case 2 uncertainties on inputs include 3% for calibration gas and 5% for instrument standard uncertainty.

Table 2. Component contributions to standard uncertainty in ER using nominal values for Case 1 (3% calibration gas and 0.5% instrument standard uncertainty) and Case 2 (3% calibration gas and 5% instrument standard uncertainty). Fixed inputs are followed by the uncertainties for two different building ventilation rates (one or eight fans) and two different ventilation rate uncertainties (25% and 5%). Concentration was varied from 0.2 to 30 ppm, and while ER and ΔER change with concentration, their relative contribution does not change.

		Case 1			Case 2		
		Uncertainty		ΔER/ER	Uncertainty		ΔER/ER
Input	Value	Absolute	(%)	Contribution	Absolute	(%)	Contribution
One fan (25% uncertainty)							
Building ventilation	33,152 m^3 h^{-1}	9,470 m^3 h^{-1}	28.6%	98.9%	9,470 m^3 h^{-1}	28.6%	96.0%
Gas concentration	0.2 ppm	<0.1 ppm	3.0%	1.1%	0.1 ppm	5.8%	4.0%
Emission rate	0.0047 kg h^{-1}	0.0013 kg h^{-1}	28.7%		0.0014 kg h^{-1}	29.2%	
Gas concentration	30 ppm	0.9 ppm	3.0%	1.1%	1.7 ppm	5.8%	4.0%
Emission rate	0.7041 kg h^{-1}	0.202 kg h^{-1}	28.7%		0.2053 kg h^{-1}	29.2%	
One fan (5% uncertainty)							
Building ventilation	33,152 m^3 h^{-1}	1,901 m^3 h^{-1}	5.7%	78.0%	1,901 m^3 h^{-1}	5.7%	49.2%
Gas concentration	0.2 ppm	<0.1 ppm	3.0%	22.0%	0.1 ppm	5.8%	50.8%
Emission rate	0.0047 kg h^{-1}	0.0003 kg h^{-1}	6.5%		0.0004 kg h^{-1}	8.2%	
Gas concentration	30 ppm	0.9 ppm	3.0%	22.0%	1.7 ppm	5.8%	50.8%
Emission rate	0.7041 kg h^{-1}	0.0457 kg h^{-1}	6.5%		0.0576 kg h^{-1}	8.2%	
Eight fans (25% uncertainty)							
Building ventilation	265,213 m^3 h^{-1}	26,786 m^3 h^{-1}	10.1%	91.7%	26,786 m^3 h^{-1}	10.1%	75.0%
Gas concentration	0.2 ppm	<0.01 ppm	3.0%	8.3%	0.01 ppm	5.8%	25.0%
Emission rate	0.0376 kg h^{-1}	0.0040 kg h^{-1}	10.5%		0.0044 kg h^{-1}	11.7%	
Gas concentration	30 ppm	0.9 ppm	3.0 %	8.3%	1.7 ppm	5.8 %	25.0%
Emission rate	5.633 kg h^{-1}	0.594 kg h^{-1}	10.5%		0.657 kg h^{-1}	11.7%	

performance curve was obtained from *in situ* calibration (Gates et al., 2004) is 5%, and results in a combined standard uncertainty of 3% to 6% (Case 1) and 6% to 7% (Case 2). The uncertainty estimates in the right plot in figure 1 (Case 2) establish the effect of increasing concentration measurement standard uncertainty from 0.5% to 5%, where 5% was the threshold value that triggered an instrument recalibration in the referenced emissions study. For this scenario, combined standard uncertainty in ER increases very little, indicating that ventilation rate uncertainty is the primary influence.

Cases 1 and 2 also provide insight into what happens if fan ventilation rate standard uncertainty is increased to 25%, for example, if a large number of fans were not calibrated but instead measured via hot wire anemometer or some less accurate methodology. A 25% fan ventilation standard uncertainty results in a combined standard uncertainty in ER approaching 30% for lower ventilation rates and 12% to 13% at the highest ventilation rate.

Further understanding of which measurement errors contribute most to overall standard uncertainty in ER is important for instrument selection and can be used to improve experimental design and measurement system implementation. Table 2 demonstrates a few nominal values of ventilation rate (one vs. eight fans) and concentration (0.2 vs. 30 ppm) as well as the values for concentration and fan ventilation standard uncertainty used in Cases 1 and 2. At low ventilation such as provided by a single fan, ER was 4.7 g h^{-1} (at 0.2 ppm) and 0.704 kg h^{-1} (at 30 ppm ammonia concentration). Standard uncertainty in the concentration measurement is 3% (Case 1) and 5.8% (Case 2). Standard uncertainty of 25% or 5% in the components that comprise building ventilation rate determination result in a 28.6% or 5.7% standard uncertainty in building ventilation rate, respectively. The effect of these factors on building emission rate uncertainty, and their relative contributions, are listed in table 2. For a single fan and 25% or 5% standard uncertainty in ventilation, the resultant combined standard uncertainty in ER is 28.7% or 6.5%, respectively. The contribution of ventilation uncertainty to the total uncertainty is 98.9% and 78.0%, respectively, for 25% or 5% standard uncertainty in ventilation. This latter value especially demonstrates the overriding effect of ventilation uncertainty on combined standard uncertainty in ER, and occurs because the concentration measurement uncertainty is quite low in Case 1. As standard uncertainty in concentration is increased to 5% (Case 2), the relative contributions of ventilation uncertainty to combined standard uncertainty in ER is 96.0% or 49.2% for ventilation standard uncertainty of 25% or 5%, respectively. An eight-fold increase in ventilation rate coupled with 25% ventilation rate uncertainty contributed 91.7% or 75.0% of combined standard uncertainty in ER for Cases 1 and 2, respectively. These percentage contributions to ΔER do not change with concentration, although ER does.

This uncertainty analysis defined a critical MQO for the study. It is clear that ventilation rate uncertainty is the critical factor in ER uncertainty for the type of concentration measurement instruments used in the Kentucky Broiler ACA Project. Prior to the implementation of the FANS methodology for building ventilation rate determination, it might be expected that in previous studies, the ventilation rate uncertainty easily exceeded 25%, and thus the range of 75.0% to 98.9% of ER uncertainty in table 2 are lower estimates of the likely contribution of ventilation uncertainty. If ventilation rate is estimated by other, less accurate, methods, then the combined standard uncertainty in ER is expected to be even greater (Xin et al., 2009).

The analysis associated with Case 2, in which the concentration measurement standard uncertainty is 5% of the concentration reading (coupled with 3% calibration gas uncertainty), is useful for evaluating alternative instru-mentation options. For example, at low ventilation rates such as are encountered in swine farrowing rooms, the uncertainty in ER is completely dominated by the ventilation uncertainty, regardless of the type of instrumentation used. Other concentration measuring instrumentation, e.g., such as was employed in the earlier IFAFS study as reported by Casey (2005), can have very different performance characteristics, for example, ±3 ppm repeatability and ±3% of full scale (model PAC III, Dräeger Safety, Inc., Pittsburg, Pa.). In that case, the contribution of that instrumentation to combined standard uncertainty in ER ranged from 23.8% to 93.3% for similar ventilation rates at 10 and 25 ppm NH_3, respectively, and with a 10% ventilation rate standard uncertainty. Thus, the conclusions drawn from this analysis are also very useful for other instrumentation whose uncertainties are primarily proportional to concentration value.

Other Factors that Influence Data Quality

Effect of Multiple Fans

Variance of an expression that is comprised of a constant multiplied by another varying quantity is the square root of the constant times the variance of the input quantity. Thus, for eight ventilation fans with identical standard component uncertainty S_F, the standard uncertainty in total building ventilation rate is $\sqrt{8}\,S_F = 2.8S_F$. However, as S_F increases with the square root of the number of fans added, the total ventilation rate increases proportionally with the number of fans, and the ratio $\Delta Q_T/Q_T$ decreases with the square root of the number of fans. For $S_F = 10\%$, the standard uncertainty in building ventilation rate (ΔQ_T in eqs. 2 and 3) will decrease to $10\% / \sqrt{8}$, or 3.6% for eight fans operating simultaneously. This effect is incorporated into the curves plotted in figure 1, where each point plotted along a curve represents the addition of an additional fan with identical performance and uncertainty characteristics. Thus, while equation 3 implies that the combined standard uncertainty in ER cannot be less than the standard uncertainties in either concentration or building ventilation, the effect of multiple fans is to reduce the relative contribution of individual fan uncertainty. In table 2, it can be seen that 98.9% and 91.7% of combined standard uncertainty in ER was associated with building ventilation rate uncertainty, assuming one or eight fans, respectively.

Effect of Fan Degradation During Grow-Out

As fans accumulate dust and are subjected to continued wear, their performance degrades. Variation between fans has been shown to exceed 24% among similar fans in the field (Casey et al., 2008) and up to 40% for the same fan over time as dirt accumulated (Ford et al., 1999). Regular cleaning between each flock was performed during the Kentucky Broiler ACA Project and confirmed with *in situ* recalibration of a random subset of fans in each building; however, quantification of degradation between calibrations, especially with respect to dirt accumulation, is not realistic and thus introduces a bias towards overestimating ventilation rate, and hence building ER. Dirt accumulation on fans during the course of a flock grow-out can result in as much as 20% overestimation of ventilation rate (Simmons and Lott, 1997; Person et al, 1979) and hence ER. Uncertainty in ER is not symmetrical around zero with this form of bias.

Effect of Neglecting Background Concentration and Air Density Effects on ER

Casey (2005) neglected background ammonia concentration (eq. 1) because the minimum detection level of the gas measurement instrument used in that study was about the same as the measured background concentration, whereas the Kentucky Broiler ACA Project (Burns et al., 2007a, 2007b) incorporated background concentration in all measurements and subtracted the ammonia flux coming into the building from that leaving the building (eq. 6). The ER methodology employed in this study properly accounts for both background concentrations and differences in air density between inlet and outlet airstreams. In this section, we outline how these simplifying assumptions affect the estimate of ER uncertainty. In general, the impact of these omissions on ER is inconsequential. This analysis is provided to document the order of magnitude of uncertainty involved when quantifying combined standard uncertainty in ER.

Neglecting a positive, non-zero background concentration can slightly overpredict ER. The magnitude of the overprediction will depend on the relative magnitudes of background and exhaust concentrations, as seen by comparing equations 1 and 6. Incorporating background concentration but neglecting the effect of air density differences will result in additional potential overprediction of ER. This combined effect is quantified in table 3 for a broad range in expected indoor and outdoor temperature and humidity ratios. The term "adjustment factor" refers to the factor as defined in equation 6 that is multiplied by background concentration. The adjustment in table 3 must be applied to the background gas concentration, not ER. The error in ER from neglecting density effects is less than 15% of the background concentration; the error in ER from neglecting background concentration depends on the magnitude of C_e and C_i. For typical expected values of inlet concentration, e.g., 1 ppm, this is a negligible error for all but the lowest exhaust concentrations, and in these cases the magnitude of ER is small even at high ventilation rates (e.g., table 2, eight fans and 0.2 ppm).The greatest overprediction in ER will occur during the coldest and driest outside conditions coupled with the warmest and most humid interior conditions, such as during winter time brooding conditions.

Table 3. Representative moist air state points for fresh and exhaust air, and the resulting adjustment factor needed if ER is computed from exhaust concentration without adjusting for air density difference.

Production Climatic Condition	Range of Humidity Ratio (g H_2O per kg dry air)		Range of Air Temperature (K)		Adjustment Factor[a]
	Inlet	Outlet	Inlet	Outlet	
Winter					
Brooding	0	20	263	306	1.150
Grow-out	2	12	263	293	1.107
Fall/spring					
Brooding	4	20	273	306	1.110
Dry interior	4	10	273	306	1.117
Grow-out	4	10	283	293	1.032
Summer					
Brooding	10	20	293	306	1.038
Grow-out	10	12	283	293	1.034

[a] Multiply inlet (background) NH_3 concentration (ppm) by the adjustment factor to account for air density differences (see eq. 6)

Conclusions

According to the analysis presented, if rigorous Quality Assurance and Quality Controls (QA/QC) protocols are properly performed and all sampling procedures and Standard Operating Procedures (SOP) are followed, the combined standard uncertainty in ER ranges from less than 6% to about 12% for building ventilation rates of 265,000 m^3 h^{-1} (156,000 cfm) to 33,000 m^3 h^{-1} (19,500 cfm) for fan ventilation standard uncertainties of 10% or less. It is less than 6% for typical values of ventilation rate, concentration measuring equipment, and component standard uncertainties employed in the Kentucky Broiler ACA Project.

Based on the results of this analysis, and for the measurement system analyzed, it can be concluded that building ER uncertainty is primarily associated with the uncertainty in building ventilation rate measurement. For example, with a single fan operating, ventilation uncertainty contributed 78% and 98.9% of ER uncertainty for a 5% and 25% standard uncertainty in fan ventilation rate measurement, respectively. The use of an accurate method for building ventilation rate measurement, such as the FANS system (Gates et al., 2004, 2005), is critical in controlling uncertainty in ER. The choice of concentration measurement instrumentation is less critical, at least for the type of instrumentation employed in this study.

The analysis indicated that there is a potential bias towards overestimation of ventilation rate as dirt accumulated on fans during flock grow-out, which could result in a bias (overprediction) of ER. To reduce the impact of this bias, all fans should be cleaned between flocks in each production house during an emissions study.

While this analysis was carried out specifically for ammonia emission measurement in commercial U.S. broiler housing, it applies equally to any gaseous contaminants that have stated accuracies in the range of this analysis, and any livestock or poultry facility that maintains a controlled environment with mechanical ventilation. To apply this analysis, the concentration standard uncertainty must be expressed as a percent of reading, specifically 0.5% or 5% as per Cases 1 and 2, respectively. To apply this analysis to particulate matter emissions in which particulate measurement uncertainty is expressed as an absolute mass concentration (e.g., 5 $\mu g\ m^{-3}$) rather than as a percent of reading, it should be restricted to concentrations greater than 500 $\mu g\ m^{-3}$, i.e., 1% of full-scale reading.

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