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## **A Portable System for Continuous Ammonia Measurement in the Field**

**Hongwei Xin, Professor**

**Akihiro Tanaka, Visiting Researcher**

Agricultural and Biosystems Engineering Dept., Iowa State University, Ames, IA 50011-3080

**Tong Wang, Assistant Professor**

Food Science and Human Nutrition Dept., Iowa State University, Ames, IA 50011

**Richard S. Gates, Professor and Chair**

Biosystems and Agricultural Engineering Dept., University of Kentucky, Lexington, KY 40546

**Eileen F. Wheeler, Associate Professor**

Agr. & Bio. Engineering Dept., The Pennsylvania State University, University Park, PA 6802

**Ken D. Casey, Research Associate**

Biosystems and Agricultural Engineering Dept., University of Kentucky, Lexington, KY 40546

**Albert J. Heber, Professor    Jiqin Ni, Tech Director    Teng Lim, Res. Associate**

Agr. & Bio. Engineering Dept., Purdue University, West Lafayette, IN 47907

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**Summary.** A portable and relatively low-cost monitoring unit (PMU) for continuous measurement of ammonia and carbon dioxide in CAFO (poultry in particular) applications has been developed and partially compared with an EPA-approved measurement method. The PMU utilizes sampling and purging cycles to overcome the sensor saturation characteristic of electro-chemical NH<sub>3</sub> sensors. Preliminary comparative results show that performance of the PMU is quite comparable to the sophisticated, higher-cost, and less portable mobile lab method. For the range of ammonia level typical of commercial poultry buildings, the PMU is expected to produce emission rate data of reasonable quality when combined with properly measured or determined building ventilation rate.

**Keywords.** Ammonia Emissions, Concentrated Animal Feeding Operations (CAFOs), Air Quality

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## INTRODUCTION

Collection of quality baseline data on aerial emissions (gases, odors, and particulates) from concentrated animal feeding operations (CAFOs) under the current U.S. production conditions is a pressing air quality issue that is facing the U.S. animal industry, academic community, and environmental regulatory agencies. The urgent need for such information is reiterated in a recent interim report by the National Academy of Science (NAS, 2002). The term CAFO emissions involve two facets. One is the emission rate (ER) or emission factor (EF) that describe the amount of aerial pollutants emitted from certain CAFO facilities to the atmosphere over some period of time; and the other is the concentration of the aerosols as they disperse progressively in the downwind direction after they leave the source. The former deals with the emissions inventory and the latter forms the basis for assessing compliance of an operation with certain outdoor air quality standards, such as the one recently recommended in the Iowa Air Quality Report (Iowa State University and the University of Iowa, 2002). The focus of this paper is to address an instrumentation issue associated with the ER/EF determination.

To obtain ER/EF, one needs to know the concentration of the aerial pollutant under concern at the source and the corresponding air exchange rate through the source. Past experiences have repeatedly shown that it is a formidable task to reliably quantify either of the two variables, on a continuous and extended basis, for CAFO applications. The challenge associated with the concentration measurement stems from the harsh nature of the sample air that analytical instruments are not typically designed to handle; the high costs of precision instruments; the large number of operations, variation among operations, and the climatic variations that should be included in such monitoring to make the results truly representative of the production practices; and yet the relatively immobility of the expensive instruments set-up once installed on site. The challenge with the airflow rate measurement lie in the large number of fans involved for some mechanically ventilated facilities, the inherent variations in airflow rate among fans due to their conditions of operation (belt tightness, degree of shutter opening, dust on blades, etc.), and high difficulty of determining ventilation rate for naturally ventilated facilities. Nonetheless, the quest continues to explore measurement apparatus that are more affordable in price while producing acceptable performance.

Two national, multi-state/agency projects, funded by the USDA Initiative for Future Agriculture and Food System (IFAFS) are currently underway in the United States to collect some of the much-needed ER data for certain species and production stages of CAFO. One project, involving six states (IA, IN, IL, MN, NC, and TX), focuses on the measurements of ER of dust, odor and gases for primarily growing-finishing swine, plus some broiler (North Carolina) and laying hen operations (Indiana). The other project, involving seven states and agencies, deals exclusively with measurement of ammonia (the most dominant noxious gas) ER from poultry facilities, i.e., broilers (Kentucky and Pennsylvania) and laying hens (Iowa and Pennsylvania). The swine/poultry project employs sophisticated mobile laboratories installed at the farm sites, one site per state and two houses per site/state. The poultry project uses less expensive and more portable units that allow for monitoring of a higher number of facilities per state. Both projects use a newly improved device for *in-situ* measurements of fan airflow rate, as described by Gates et al. (2002) and Wheeler et al. (2002). In addition, CO<sub>2</sub> balance-based building ventilation rate will be assessed for the laying hen houses according to the relationships of total heat production rate to CO<sub>2</sub> production rate for modern laying hens (W-36 breed) that are recently developed at Iowa State University (Chepete et al., 2002; Chepete and Xin, 2002).

The objective of this paper is to describe the development and operation of the concentration-monitoring unit used in the poultry-ammonia project. The unit, made from commercially available components, is used to continuously measure and record data on aerial ammonia (NH<sub>3</sub>) and carbon dioxide (CO<sub>2</sub>) levels (ppm) in poultry buildings.

## DEVELOPMENT OF THE MONITORING UNIT

### Evaluation and Selection of Ammonia Monitors

Past experiences of the authors and other researchers (Wilhelm, 1999) indicate that when properly calibrated and operated, electro-chemical (EC) sensors provide reasonable measurement of ammonia ( $\text{NH}_3$ ) concentration. It is also our expectation that advancement of technology has led to further improved quality of the products. EC monitors are much more affordable and portable as compared with analyzers employing infrared, thermal oxidation, or open-path optical technologies (McCulloch and Shendrikai, 2000; Harris et al., 2001). Use of such monitoring units would allow us to collect data from a greater number of poultry houses than with a more expensive and less portable method. This led to our decision to evaluate the EC- $\text{NH}_3$  monitors. Specifically, two models of EC- $\text{NH}_3$  monitors from Draeger Safety, Inc. (GDS Houston Office, Houston, Texas<sup>1</sup>), Polytron II with low concentration (0-100 ppm) sensor (Polytron II-LC) or high concentration (0-300 ppm) sensor (Polytron II-HC) and Pac IIIH with a 0-200 ppm sensor and a  $\text{H}_2\text{S}$  filter were evaluated. The Polytron II-HC has a resolution of 5 ppm, whereas the Polytron II-LC and the Pac IIIH have a resolution of 1 ppm. The Polytron II has a 4-20 mA analog output for the sensor measurement range, whereas the Pac IIIH has an internal data storage capacity of 7,200 points. An optional software kit (GasVision software, download module cable, and 110 power adapter) is used in conjunction with the Pac IIIH for the logger programming and data retrieval.

The EC sensors have an inherent characteristic of saturation when continuously exposed to  $\text{NH}_3$ -laden air. As such, these units are designed for background ammonia monitoring, where normally no ammonia exists in the environment (Rich Wanek and Victor Hoang, Draeger Safety Inc., personal communication, 2001). When ammonia does exist the unit will detect and send out an alarm signal as specified. For the monitors to be used in continuous monitoring of  $\text{NH}_3$  in CAFO settings, the sensors must be periodically rejuvenated.

Our first evaluation was to quantify the responses of these units to continuous exposure of 45.8 ppm  $\text{NH}_3$  with  $\text{N}_2$  balance span gas ( $\pm 2\%$  accuracy) (Matheson Gas Products, Inc., Montgomeryville, PA) at a flow rate 0.5 L/min for 20 h. Data collection was done at 30-s intervals. A schematic of the evaluation setup is shown in figure 1 and the results in figure 2. As can be seen from figure 2, all three monitors had a good initial indication of the ammonia level, but quickly began to deviate from the true value. The measured values during the 20-h exposure period averaged 37.0 ( $\pm 3.1$ ) ppm for Polytron-HC, 52.8 ( $\pm 5.5$ ) ppm for Polytron-LC, and 50.7 ( $\pm 5.6$ ) ppm for Pac III. This result confirms the belief about the inadequacy of continuously exposing EC sensors to  $\text{NH}_3$ -laden air. Repetition tests yielded the same conclusion.

To rejuvenate the sensors, zero gas is to be periodically introduced to the units, also known as purging. To evaluate the time requirement of purging and sampling, we first evaluated the response time of the sensors to step changes in gas concentrations. The results are summarized in Table 1. The time taken for the readings to change from 0 ppm ( $\text{N}_2$  gas) to 45.8 ppm (span gas) was 4 minutes for Polytron-HC and 1 minute for Polytron-LC and Pac III. In comparison, the time taken for the readings to change from 45.8 ppm to 0 ppm, i.e., purging time, ranged from 140 sec for Polytron-HC to 480 sec for Pac III. Thus, the results indicated that a combination of 4 min sampling and 6 min purging for Polytron-HC, and 2 min sampling and 8 min purging for Polytron-LC and Pac III would be sufficient and were further evaluated. Figure 3 shows the responses of the three monitors to the sampling-purging cycles. It can be noted that readings by the Polytron-HC tended to fluctuate the most both within and between cycles. Readings of the Polytron-LC drifted down rapidly upon reaching the maximum span level, even though the readings

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<sup>1</sup> Mention of vendor or product names is for presentation clarity and does not imply endorsement by the authors or their affiliations, or exclusion of other suitable products.

during the purging phase were stable and accurate. By comparison, readings of the Pac III were most steady during both the sampling and purging phases, with the tendency of overshooting below zero during the initial part of the purging phase.

Table 1. Summary of response time (s) of Polytron-HC, Polytron-LC, PAC III ammonia (NH<sub>3</sub>) monitors to changes in NH<sub>3</sub> concentrations from 0 to 45.8 ppm or from 46.8 to 0 ppm.

Repetition	From 0 ppm to 45.8 ppm			From 45.8 ppm to 0 ppm		
	Polytron-HC	Polytron-LC	PAC III	NH <sub>3</sub> -HC	NH <sub>3</sub> -LC	PAC III
1	230	50	60	140	420	490
2	310	60	50	180	370	490
3	220	60	50	120	540	490
4	200	70	60	120	360	450
Mean	240	60	55	140	423	480

Next, a 48-h evaluation of the Pac III unit was performed to further quantify the responses of the sensor to sampling-purging cycles. The choice of 48 h period was based on the intended measurement duration per monitoring episode in the field. The sampling and purging time was increased to 5 and 10 min, respectively, in anticipation of higher NH<sub>3</sub> level, which could increase the purging time requirement. Also, fresh air instead of N<sub>2</sub> gas was used for purging to represent the field monitoring situation. Data collection was done at 30-s intervals (at which the Pac III can store about 68 h of data). Figure 4 shows the dynamic profile. The maximum concentrations of each sampling and purging cycle ranged from 46 to 48 ppm during the first 18 h, and gradually increased to 51 ppm by the end of the 48-h period. The concentration of fresh air was shown slightly negative (-1 to -2 ppm) during the period of 6 to 13 h. After that, the readings for fresh air would rise to 4-5 ppm after having reached 0 ppm. The time of stabilized readings at the span concentration also progressively got shorter. To better visualize the dynamic profiles, 1-hr sections of the data near the beginning, middle, and end of the experimental duration are plotted in figure 5, 6 and 7, respectively.

The question is then “How should the data be analyzed to minimize/eliminate the effects of the temporal shifting?” To answer this question, the readings corresponding to the span gas sampling were taken as 5 min, first 3 min or last 3 min averages and the maximum of each sampling-purging cycle, and the results are shown in figure 8. These temporal average and maximum values followed the similar trend as seen in figure 2, and have a tendency of overestimating the concentrations over time. To correct this, the average or maximum readings for the corresponding purging phases are subtracted from those of the sampling phases, and the results are shown in figure 9. The mean differential concentrations were 44.9 ( $\pm 1.0$  S.D.) ppm using the 5 min average, 45.3 ( $\pm 0.9$ ) ppm using the first 3 min average, 44.7 ( $\pm 1.5$ ) ppm using the last 3 min average, and 46.6 ( $\pm 0.7$ ) ppm using the maximum. Compared with the span gas concentration of 45.8 ppm, differentials of the first 3-min averages or the maximums gave the discrepancies of less than 1 ppm. Hence, either one of the two may be used for the purpose of determining ammonia concentration difference between the exhaust air and the incoming (fresh) air in the field.

### The Portable Dual-Gas Monitoring Unit (PMU)

Information about the components of the portable NH<sub>3</sub> and CO<sub>2</sub> monitoring unit (PMU) is presented in Table 2. Schematic illustrations of the components and wiring connections are shown in figures 10 and 11. A photographical view of the unit inside the metal enclosure is shown in figure 12.

Table 2. List of components of the portable ammonia (NH<sub>3</sub>) and carbon dioxide (CO<sub>2</sub>) measurement unit

Item	Vendor/Brand	Description	Cat. Number	Qty/pk	Unit price	Qty	Subtotal
Twin Timer	Omron	24V AC/DC	H3CR-F8 AC/DC24		\$64.13	1	\$64.13
8 pin socket	Omron	for twin timer	P2CF-08		\$4.36	1	\$4.36
Dust filter	Cole-Parmer	Compressed-air filter	U-02917-00		\$37.25	3	\$111.75
Pump	Cole-Parmer	0.5CFM, 115V	U-79610-00		\$305.00	1	\$305.00
Straight connector	Cole-Parmer	4-6 mm, White PP	U-06288-10	10	\$8.50	1	\$8.50
Elbow connectors	Cole-Parmer	6mm, Clear PP	U-06285-20	20	\$13.50	1	\$13.50
T connectors	Cole-Parmer	6mm, Clear PP	U-06294-20	20	\$21.25	1	\$21.25
Y connectors	Cole-Parmer	6mm, Clear PP	U-06295-20	20	\$21.25	1	\$21.25
NPT male pipe adapters	Cole-Parmer	1/4"x1/4", Natural PP	U-30610-38	10	\$5.75	1	\$5.75
NPT male adapter elbows	Cole-Parmer	1/4"x1/4", Natural PP	U-30610-56	10	\$9.25	1	\$9.25
NPT male adapter elbows	Cole-Parmer	1/8"x1/4", Natural PP	U-30610-54	10	\$9.25	1	\$9.25
Straight connector	Cole-Parmer	1/4"	U-06463-15	10	\$4.25	1	\$4.25
Elbow connectors	Cole-Parmer	1/4"	U-06467-10	10	\$6.50	1	\$6.50
T connectors	Cole-Parmer	1/4"	U-06455-15	10	\$6.25	1	\$6.25
Flow meter	Dwyer	100-1000 cc/min	RMA-13-SSV		\$27.50	2	\$55.00
Flow meter	Dwyer	1-10 L/min	RMA-21-SSV		\$27.50	1	\$27.50
Power Supply	Radio Shark	12 VDC, 1500 mA			\$15.00	1	\$15.00
Power Supply	Radio Shark	24 VAC, 1000 mA			\$15.00	1	\$15.00
Fuse case & fuse	Radio Shark				\$4.00	1	\$4.00
Metallic enclosure	Kriz Davis Co.	24"x24"x8"			\$191.80	1	\$191.80
Mounting plate	Kriz Davis Co.	21"x21" for enclosure			\$29.50	1	\$29.50
Terminal block	Kriz Davis Co.				\$4.00	1	\$4.00
Pac IIIH unit	Drager Safety	Pac III Hygiene unit	4530011		\$420.75	2	\$841.50
Pac III ammonia sensor	Drager	NH <sub>3</sub> sensor, 0-200 ppm	4595407		\$335.75	2	\$671.50
B2T filter	Drager	H <sub>2</sub> S filter	6809198		\$19.15	2	\$38.30
Pac III sensor adaptor	Drager	Sensor adaptor	6806291		\$63.75	2	\$127.50
CO <sub>2</sub> sensor	Vaisala, Inc.	CO <sub>2</sub> transmitter	GMT222		\$637.50	1	\$637.50
Backlit digital display	Vaisala, Inc.				\$85.00	1	\$85.00
Field check adapter	Vaisala, Inc.				\$55.25	1	\$55.25
<b>Total</b>							<b>\$3,389</b>

Optional items: CO<sub>2</sub> calibrator (model GMK220, Vaisala Inc.) @ \$1,535

One-time cost: Software kit for Pac III H @ \$350

Two Pac IIIH units are used to provide a backup and mutual check on the ammonia measurement. The adjustable on-off cycle timer is used to set and control the sampling and purging time (e.g., 5 min on for sampling, followed by 10 off for purging) by controlling the operation of the 3-way solenoid valve. Timing of the on-off switching is monitored and recorded through a voltage divider that is connected to the extra set of contacts of the DPST timer relay. Output of the voltage divider (0 when off/purging and 1.2VDC when on/sampling) is connected to a portable data logger (HOBO<sup>®</sup> 4-Channel External Indoor Logger, Onset Computer Corp., Pocasset, MA).

The use of the by-pass line after the solenoid valve serves two purposes: 1) shortening the residence time of the sampling or purging air in the delivery line, and 2) to reduce the work load for the air pump. The air pump delivers approximately 11 L/min, although the NH<sub>3</sub> and CO<sub>2</sub> sensors need only 0.5-0.6 l/min flow rate. Control of the by-pass and the flow through the sensors is done via the flow meters. The air pump was placed downstream of the NH<sub>3</sub> loggers to avoid its potential influence on the integrity of the air sample – NH<sub>3</sub> content. The pump is very quiet and generating little heat, which is beneficial for the monitoring system because the NH<sub>3</sub> sensor is somewhat sensitive to ambient temperature. With the combination of this low-heat pump and metal enclosure, the temperature rise inside the enclosure relative to the ambient is generally less than 2°C. Similar temperature rise was found using a plastic enclosure.

Initially no upstream air filter for the solenoid valve was used for the same reason of preserving the sample – dust content integrity (because dust may carry ammonia with it). However, field test revealed accumulation of impurities (dust or dead flies) in the valve, which adversely affected the integrity of the sample or purging air. To avoid such accumulation, an upstream filter for both sample and purging lines are now installed and periodically replaced. The pertinent filters are also replaced when moving the unit between the sites for bio-security reasons.

The CO<sub>2</sub> transmitter used in the unit is an infrared type with a measurement range of 0-5,000 or 0-10,000 ppm and analog output of 0-20 mA (Model GMT222, Vaisala Inc., Woburn, MA). Initially the transmitter was installed in the upstream of the air pump. However, leakage around the sensor probe adaptor proved to be difficult to seal, which made it necessary to be placed downstream of the pump (fig. 10). An optional calibrator (model GMK220, Vaisala Inc.) is used for occasional calibration of the CO<sub>2</sub> sensors.

All the components except for the pump and power supply packs are mounted on a metal plate (Table 2) via screw, Velcro or built-in mounting clip (fig. 12). This arrangement allows easy transportation of the device after the enclosure has been mounted onto the wall of a poultry barn.

Cost of the materials for one PMU is estimated to be around \$3,400. This price is much lower than that for a set of thermal oxidizer (chemiluminescence) NH<sub>3</sub> analyzer about (\$16,500) and an infrared CO<sub>2</sub> analyzer (about \$6,000). Admittedly, the resolution of the EC-NH<sub>3</sub> sensor (1 ppm) is considerably lower than that of the thermal oxidizer counterpart (down to ppb level). When addressing building emission rate, however, the relatively large uncertainty associated with determination of the building ventilation rate generally makes the difference in resolution a trivial issue. Of course, when dealing with measurement of downwind concentration from the source, employment of the more sensitive thermal oxidizer analyzer would be definitely necessary.

## **OPERATION OF THE MONITORING UNIT**

Before dispatched into the field, all Pac III units are calibrated and programmed to collect data at 30 s intervals. The units will be turned on upon arrival at the field site. The CO<sub>2</sub> monitors are checked against the zero and span calibration gases, and calibrated if necessary. The data logger for the CO<sub>2</sub> monitor output and the timer switching measurement is also programmed to collect data at 30 s intervals with a delayed start of specified date and time. At the end of each 3-d monitoring episode, the instruments are

brought back to the campus lab, data downloaded, sensors checked, calibrated or replaced as needed. The units are then cleaned and disinfected to the extent possible without adversely affecting the integrity of the sensors before they are sent to another field site. An example of the monitored ammonia concentration in a high-rise layer house with the unit described above is shown in figure 13.

To evaluate the performance of the PMU, field test has been in progress that compares the PMU with an EPA-approved method of chemiluminescence  $\text{NH}_3$  analyzer (model 17C, Thermo-Environmental Instruments, Franklin, MA) that is an integral part of the Purdue University mobile laboratory installed at a laying hen facility (figure 14) near West Lafayette, Indiana. The mobile lab takes readings at 1-min intervals continuously, whereas the PMU takes data using 5/10-min sampling and purging cycles. The maximum readings of the 5-min sampling periods are taken as the PMU output; and the corresponding 5-min averages from the mobile lab measurements are used as the references. The relationship of data from the two measurement approaches is shown in figures 15 and 16, and summarized in Table 3. These data, though preliminary, show very reasonable agreement between the two approaches. The test will continue through the next fall and winter.

Table 3. Preliminary result on comparison of ammonia concentration measurements using the portable, purging electro-chemical (EC) sensor unit (PMU) vs. chemiluminescence (CL) analyzer used in the mobile lab at Purdue University (Test period: May 16-20, 2002)

<b>Statistic</b>	<b>EC-NH<sub>3</sub> PMU</b>	<b>CL NH<sub>3</sub> Unit</b>
Mean, ppm	29.5	29.0
Minimum, ppm	18.0	18.9
Maximum, ppm	38.0	36.7
Number of observations	298	298
S.D., ppm	3.2	3.5
S.E., ppm	0.2	0.2

## **CLOSURE**

A portable and relatively low-cost monitoring unit (PMU) for continuous measurement of ammonia and carbon dioxide in CAFO (poultry in particular) applications has been developed and partially compared with an EPA-approved measurement method. The unit utilizes sampling and purging cycles to overcome the sensor saturation characteristic of electro-chemical  $\text{NH}_3$  sensors. Preliminary comparative results show that performance of the unit is quite comparable to the more sophisticated, higher-cost, and less portable mobile lab method. For the range of aerial ammonia typical of commercial poultry buildings, the unit is expected to produce emission rate data of reasonable quality when combined with properly measured or determined building ventilation rate. It should also be noted that the PMU described in this paper is not intended for assessment of outdoor air quality standard compliance where high sensitivity to the gas (ppb levels) is required.

## **ACKNOWLEDGEMENTS**

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## REFERENCES

- Chepete, H. J., H. Xin, R.S. Gates, and M.C. Puma. Heat and moisture production of poultry and their housing systems: *Pullets and layers*. *Transactions of the ASHRAE* (in review)
- Chepete, H. J. and H. Xin. 2002. Heat and moisture production of poultry and their housing systems: *Molting layers*. *Transactions of the ASHRAE* (in review)
- Gates, R. S., J. D. Simmons, K. D. Casey, T. Greis, H. Xin, E. F. Wheeler, C. King, and J. Barnett. 2002. Fan assessment numeration system (FANS) design and calibration specifications. Technical paper No. 024124. American Society of Agricultural Engineers, St. Joseph, MI: ASAE
- Harris, D. B., Thompson, Jr., Vogel, C. A., Hashmonay, R. A., Natschke, D. A., Wagoner, K. and Yost, M.G. 2001. Innovative approach for measuring ammonia and methane fluxes from a hog farm using open-path fourier transform infrared spectroscopy. *Proceedings of the 94<sup>th</sup> Annual Conference of the Air & Waste Management Association*, Orlando, FL, June 24-28, 2001.
- Iowa State University and the University of Iowa. 2002. Iowa Concentrated Animal Feeding Operation Air Quality Study – Final Report. <http://www.public-health.uiowa.edu/ehsrc/CAFOstudy.htm>
- McCulloch, R. B. and A. D. Shendrikar. 2000. Concurrent atmospheric ammonia measurements using citric-acid-coated diffusion denuders and a chemiluminescence analyzer. *Atmospheric Environment* 34: 4957-4958.
- National Academy of Science (2002). The Scientific basis for estimating emissions from animal feeding operations: Interim report. <http://bob.nap.edu/books/030908461X/html/>
- Wheeler, E. F., R. S. Gates, H. Xin, J. Zajackowski, and C. D. Casey. 2002. Field estimation of ventilation capacity using FANS. Technical paper No. 024125. American Society of Agricultural Engineers, St. Joseph, MI: ASAE
- Wilhelm, L. R., J. M. Milner, S. D. Snyder, D. McKinney. 1999. An instrumentation system for environmental measurements in poultry and swine housing. Technical paper No. 993192. American Society of Agricultural Engineers, St. Joseph, MI: ASAE



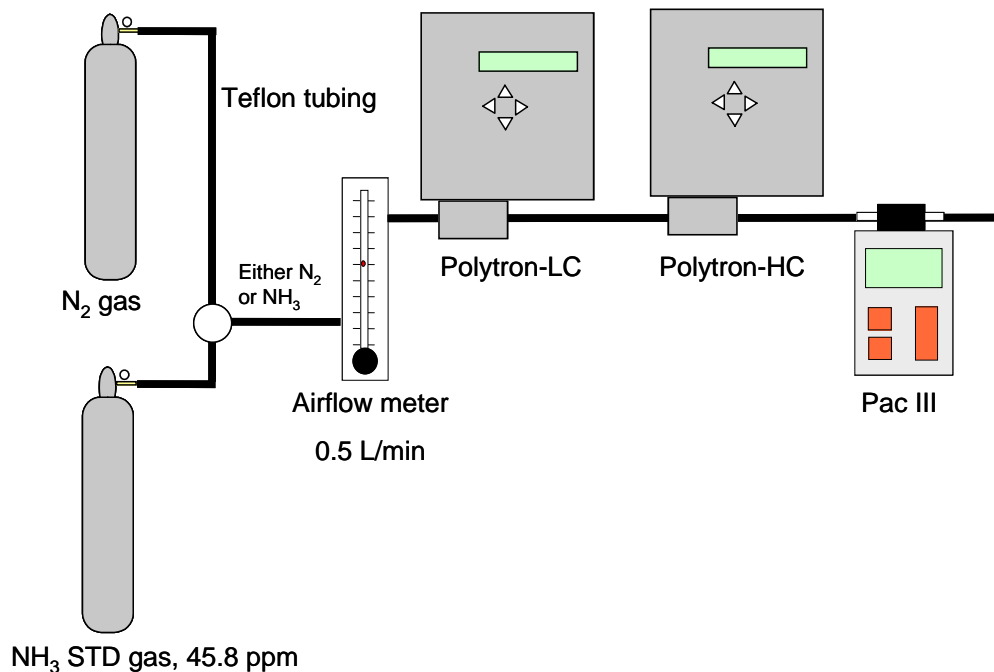


Figure 1. Schematic representation of the ammonia monitors evaluation setup.

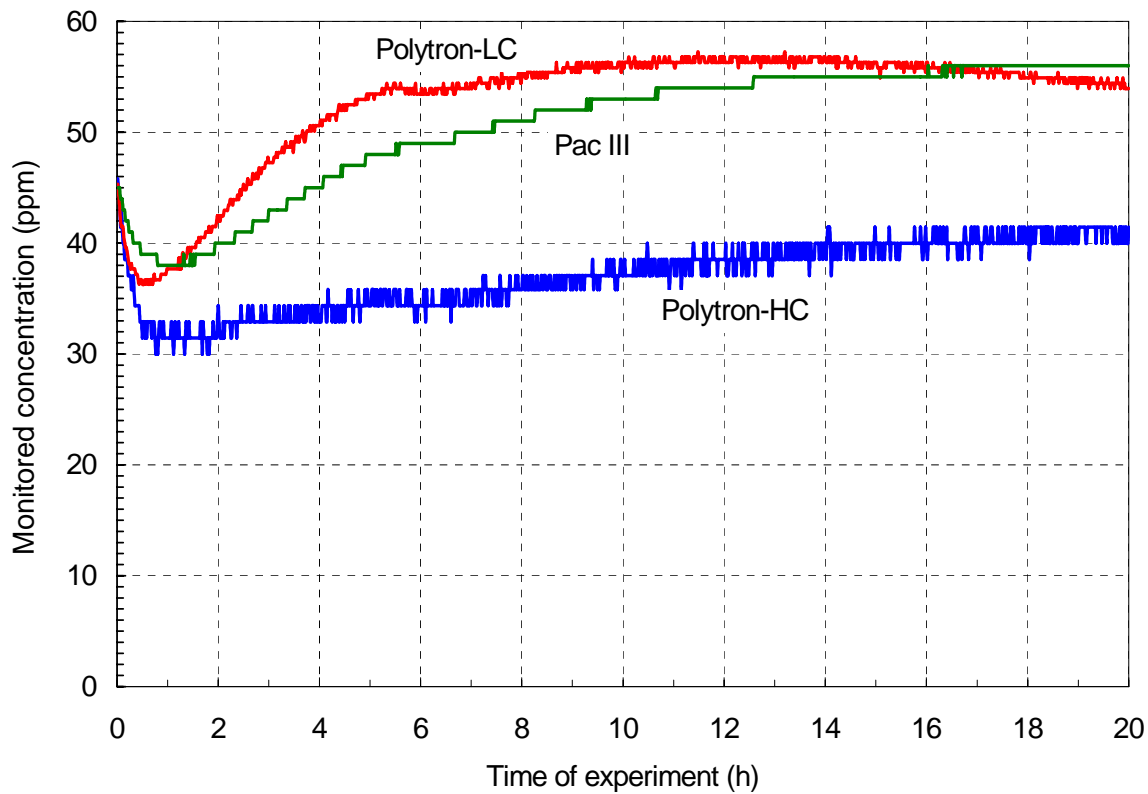


Figure 2. Temporal responses of Polytron-HC, Polytron-LC and Pac III to continuous exposure of 45.8 ppm ammonia (N<sub>2</sub> balance) calibration gas.

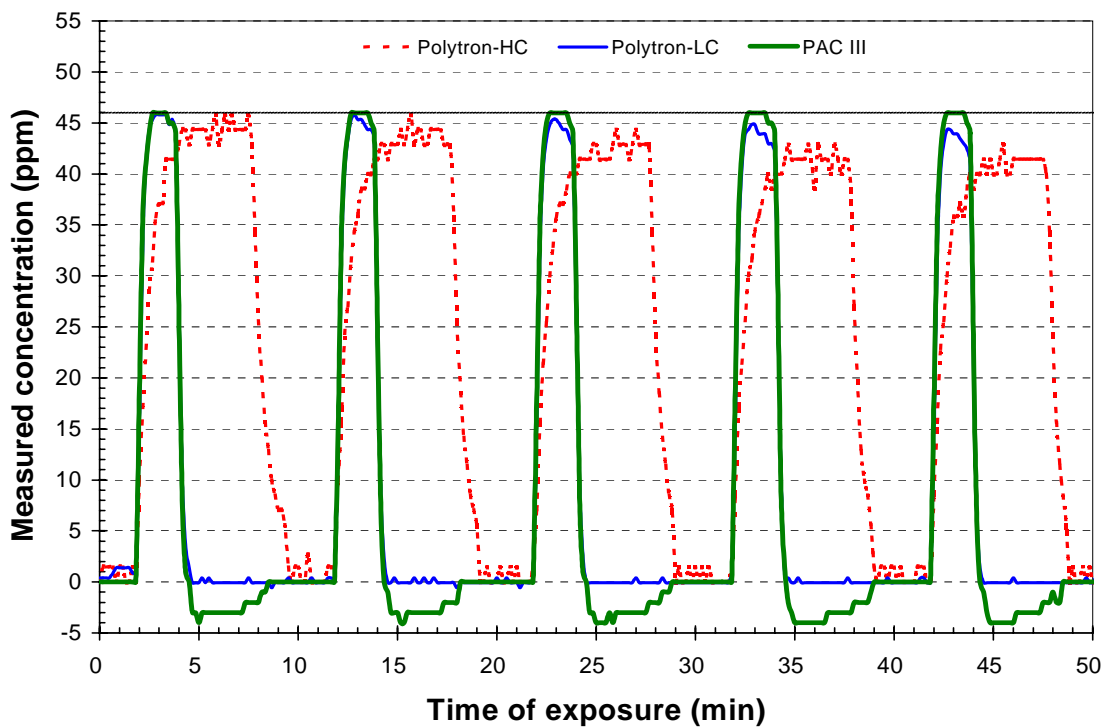


Figure 3. Responses of Polytron-HC, Polytron-LC and Pac III to intermittent exposure of 45.8 ppm ammonia ( $N_2$  balance) and zero ( $N_2$ ) gases.

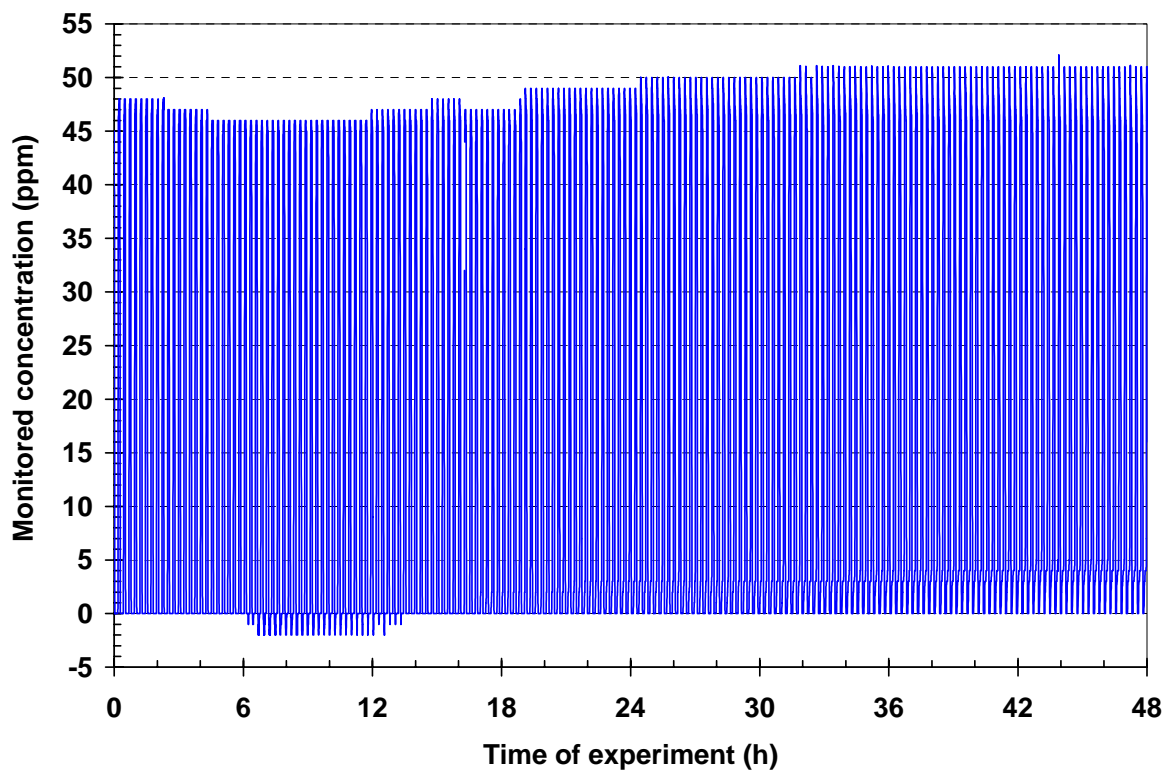


Figure 4. Response profile of the Pac III ammonia monitor to 5 min sampling (45.8 ppm  $NH_3$ ) and 10 min purging ( $N_2$ ) cycles during a 48-h testing period.

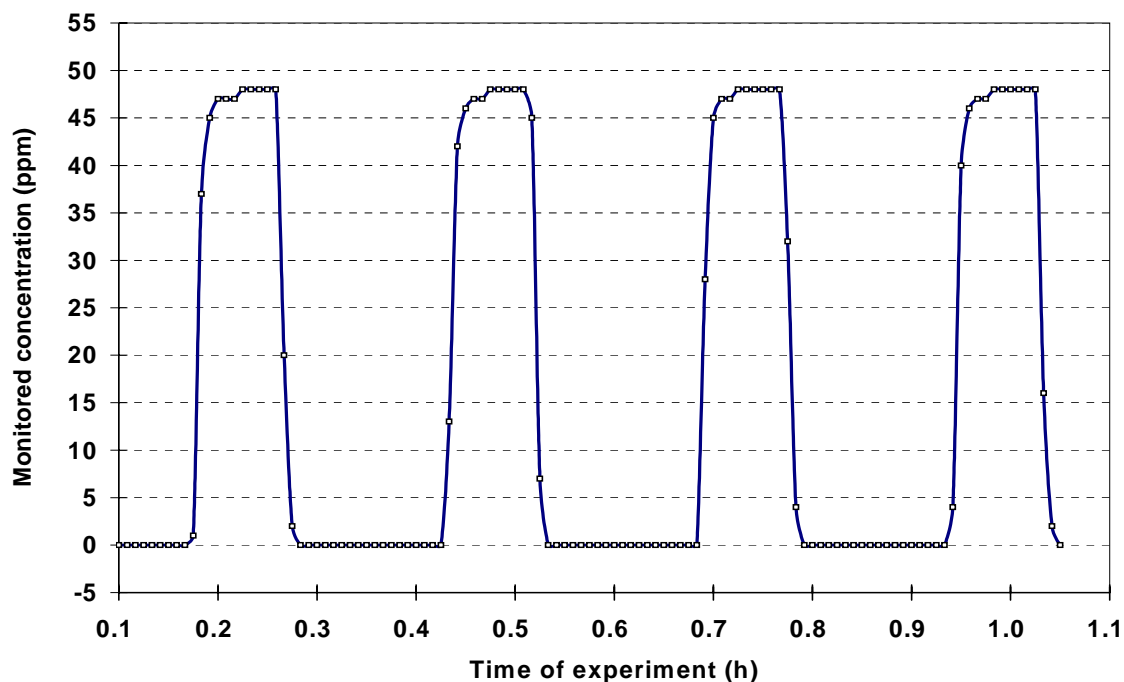


Figure 5. Response profile of the Pac III ammonia monitor to 5 min sampling (45.8 ppm  $\text{NH}_3$ ) and 10 min purging ( $\text{N}_2$ ) cycles during the first hour of the testing period.

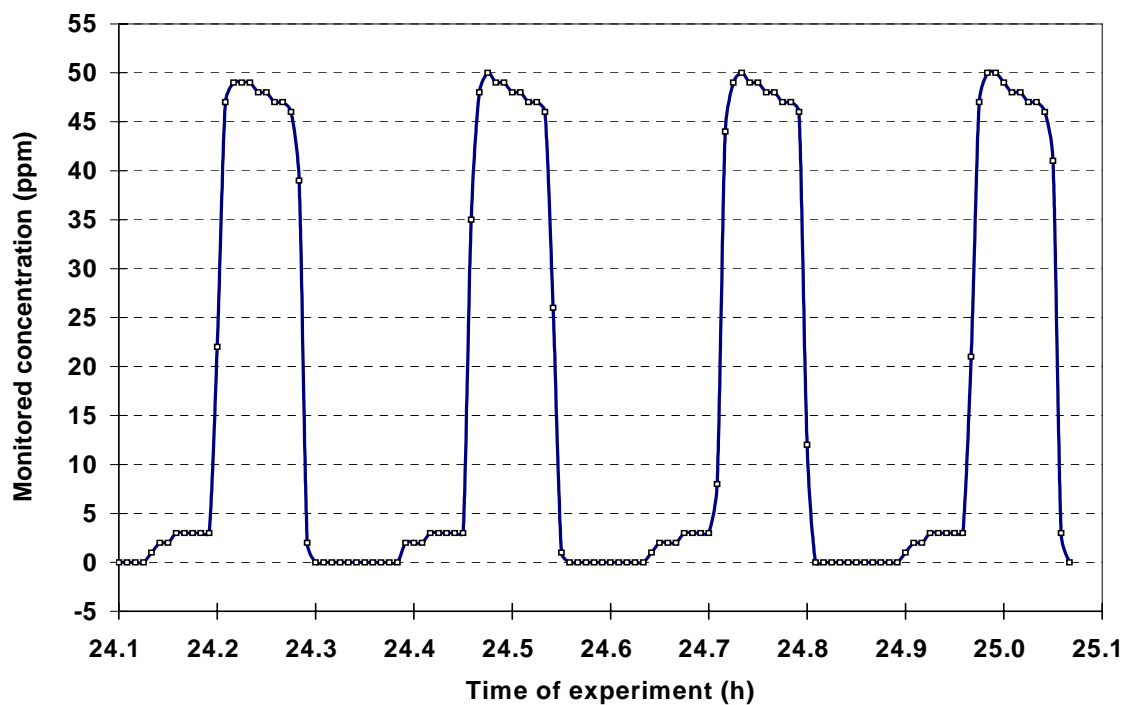


Figure 6. Response profile of the Pac III ammonia monitor to 5 min sampling (45.8 ppm  $\text{NH}_3$ ) and 10 min purging ( $\text{N}_2$ ) cycles during the 24-25 h of the testing period.

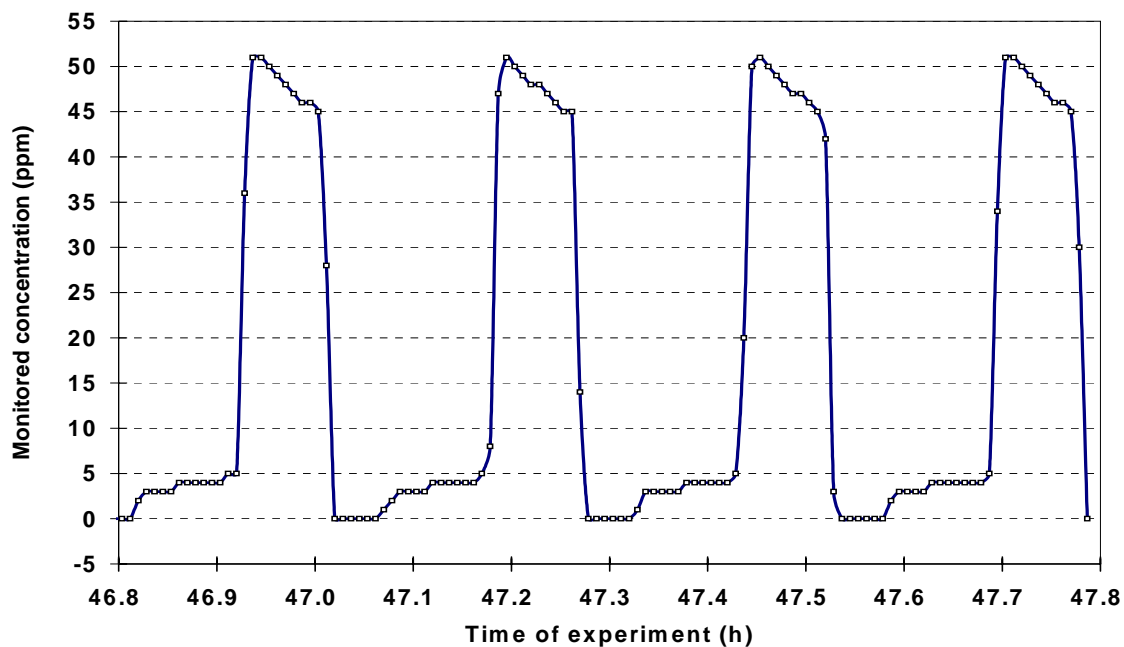


Figure 7. Response profile of the Pac III ammonia monitor to 5 min sampling (45.8 ppm  $\text{NH}_3$ ) and 10 min purging ( $\text{N}_2$ ) cycles during the 47-48 h of the testing period.

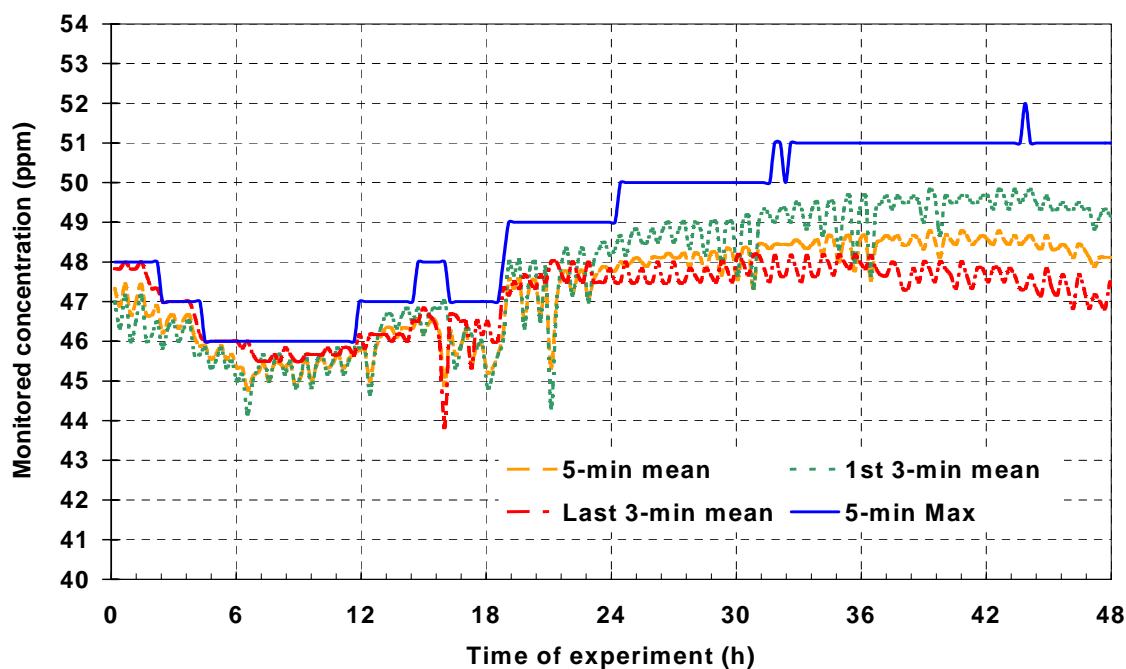


Figure 8. Measured concentrations of the  $\text{NH}_3$  span gas (45.8 ppm) using various calculation scenarios for the Pac III ammonia monitor undergoing 5 min sampling and 10 min purging cycles during the 48 h testing period.

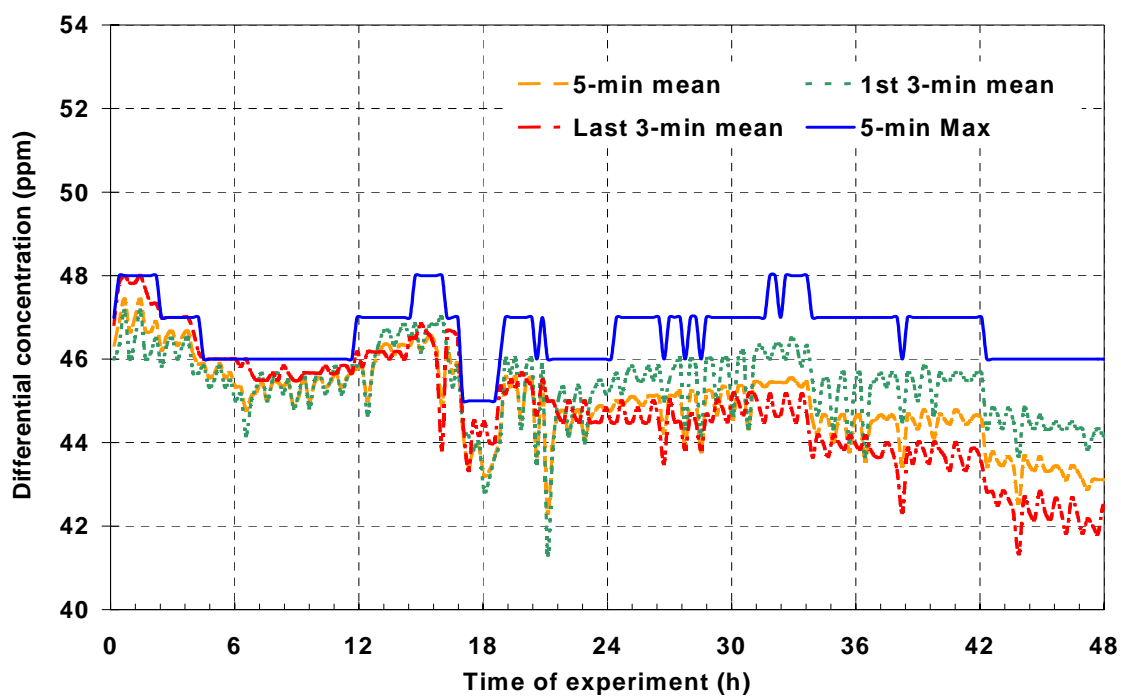


Figure 9. Measured concentrations of the  $\text{NH}_3$  span gas (45.8 ppm) using various differential calculation scenarios for the Pac III ammonia monitor undergoing 5 min sampling and 10 min purging cycles during the 48 h testing period.

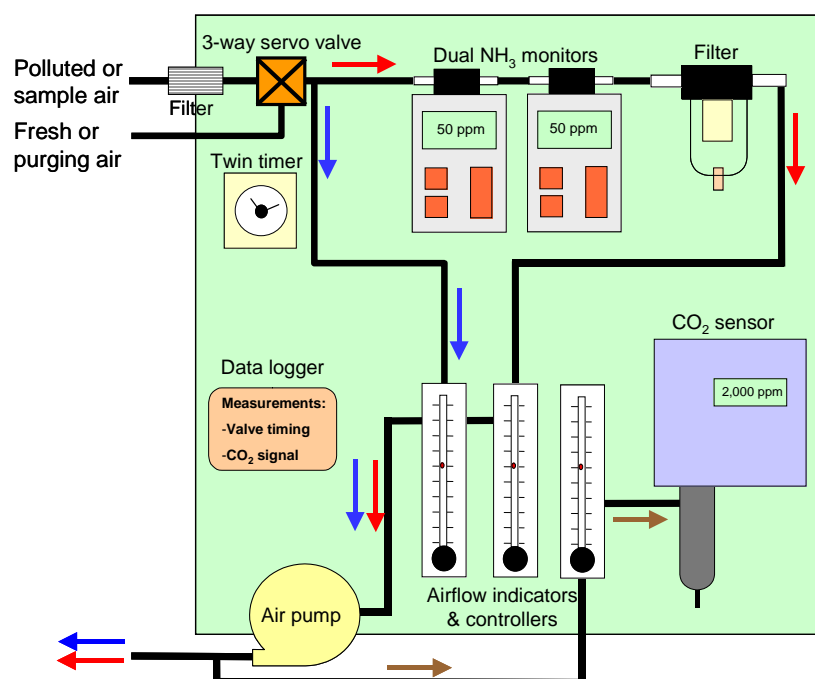


Figure 10. Schematic illustration of the components and connections of the portable  $\text{NH}_3$  and  $\text{CO}_2$  measurement unit described in this paper.

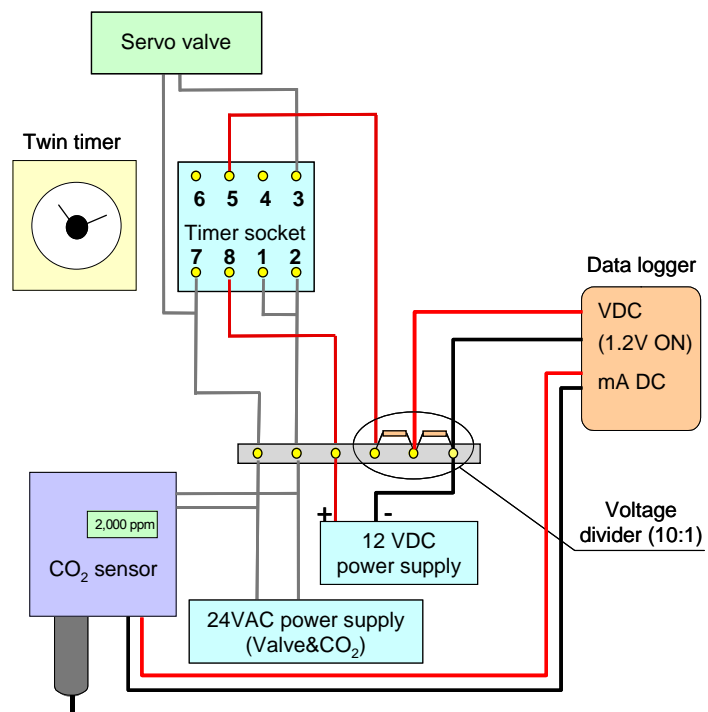


Figure 11. Schematic representation of the wiring diagram depicting the control of servo valve, monitoring of switch timing, and output of the CO<sub>2</sub> sensor.

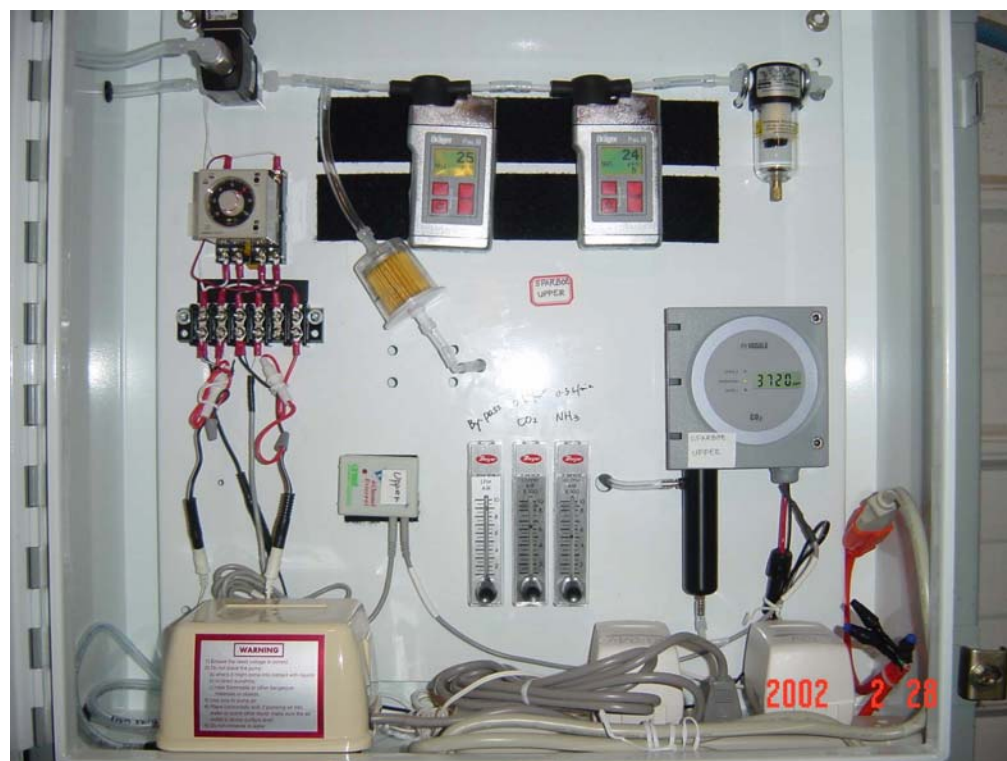
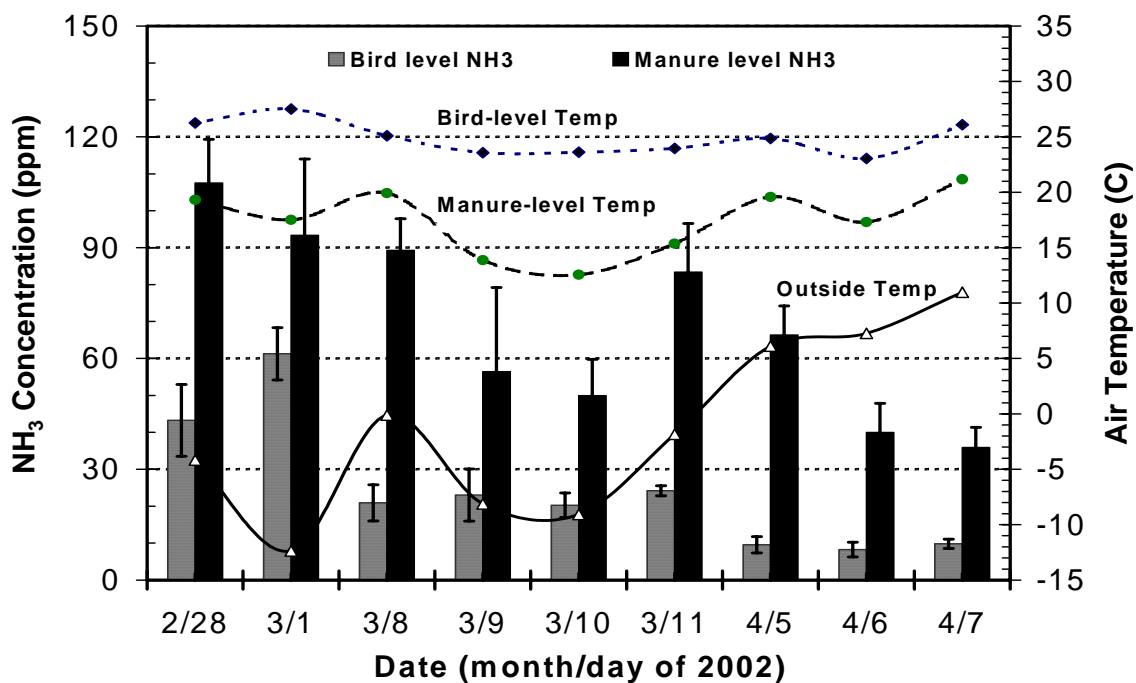


Figure 12. A photographical view of the ammonia and carbon dioxide measurement unit.



**Figure 13.** Daily ammonia concentrations at both bird and exhaust levels in a high-rise layer house as measured with the monitoring unit described in this paper.



**Figure 14.** The Purdue University mobile lab for emission measurement installed at a laying hen facility where side-by-side comparison between the ISU portable dual-gas monitoring unit and the chemiluminescence analyzer of the mobile lab is made.

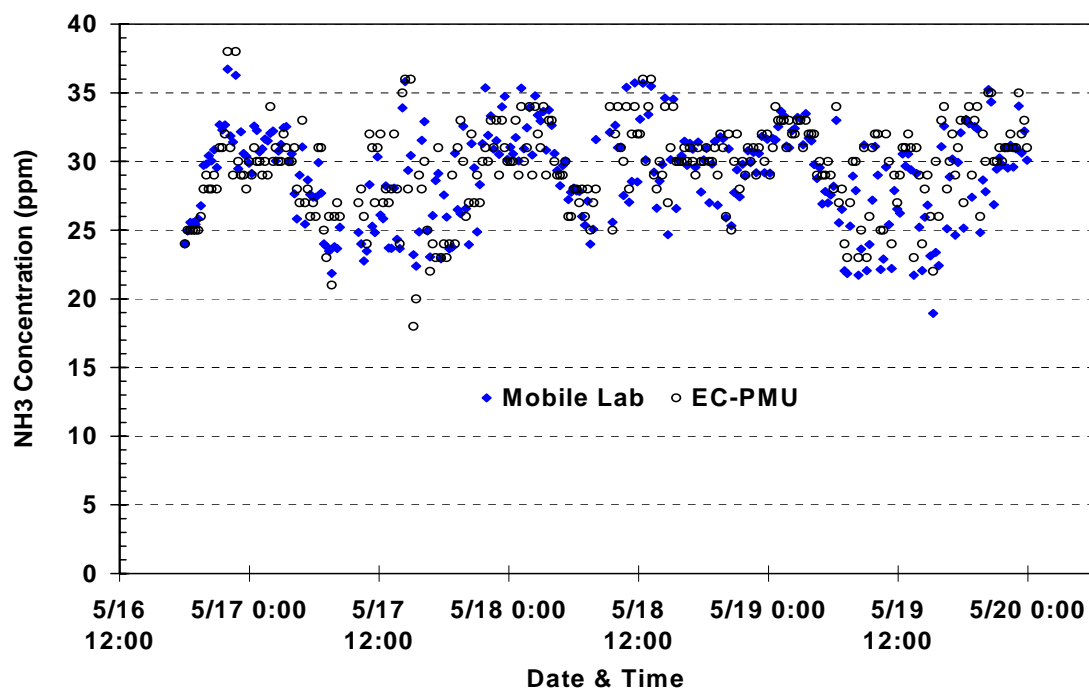


Figure 14. Ammonia concentration in the exhaust air of a laying hen house as measured by the mobile lab (thermal oxidizer analyzer) and by the portable monitoring unit (PMU).

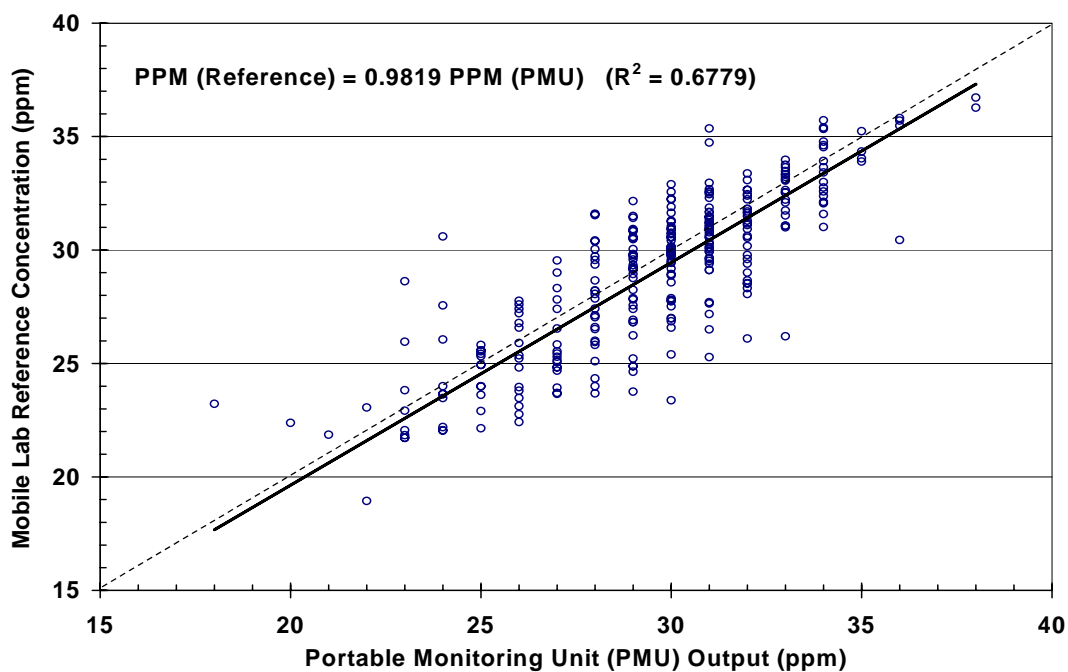


Figure 15. Relationship between NH<sub>3</sub> readings from the Purdue mobile lab (thermal oxidizer analyzer) and the portable monitoring unit (PMU) described in this paper.