CO_2 MONITORING FOR DEMAND CONTROLLED VENTILATION IN COMMERCIAL BUILDINGS

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March 17, 2010

The research reported here was supported by the California Energy Commission Public Interest Energy Research program award number 600303000 and by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of the Building Technologies Program, U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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Report to the California Energy Commission
Public Interest Energy Research Program

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Agreement No. 600303000
PIER Subject Area: Buildings End Use Energy Efficiency Program

DISCLAIMER

ACKNOWLEDGMENT OF FINANCIAL SUPPORT

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EXECUTIVE SUMMARY

Carbon dioxide (CO_2) sensors are often deployed in commercial buildings to obtain CO_2 data that are used, in a process called demand-controlled ventilation, to automatically modulate rates of outdoor air ventilation. The objective is to keep ventilation rates at or above design specifications and code requirements and also to save energy by avoiding excessive ventilation rates. Demand controlled ventilation is most often used in spaces with highly variable and sometime dense occupancy. Reasonably accurate CO_2 measurements are needed for successful demand controlled ventilation; however, prior research has suggested substantial measurement errors. Accordingly, this study evaluated: (a) the accuracy of 208 CO_2 single-location sensors located in 34 commercial buildings, b) the accuracy of four multi-location CO_2 measurement systems that utilize tubing, valves, and pumps to measure at multiple locations with single CO_2 sensors, and c) the spatial variability of CO_2 concentrations within meeting rooms.

The field studies of the accuracy of single-location CO_2 sensors included multi-concentration calibration checks of 90 sensors in which sensor accuracy was checked at multiple CO_2 concentrations using primary standard calibration gases. From these evaluations, average errors were small, -26 ppm and – 9 ppm at 760 and 1010 ppm, respectively; however, the averages of the absolute values of error were 118 ppm (16%) and 138 ppm (14%), at concentrations of 760 and 1010 ppm, respectively. The calibration data are generally well fit by a straight line as indicated by high values of R^2. The Title 24 standard specifies that sensor error must be certified as no greater than 75 ppm for a period of five years after sensor installation. At 1010 ppm, 40% of sensors had errors greater than ±75 ppm and 31% of sensors has errors greater than ±100 ppm. At 760 ppm, 47% of sensors had errors greater than ±75 ppm and 37% of sensors had errors greater than ±100 ppm. A significant fraction of sensors had errors substantially larger than 100 ppm. For example, at 1010 ppm, 19% of sensors had an error greater than 200 ppm and 13% of sensors had errors greater than 300 ppm.

The field studies also included single-concentration calibration checks of 118 sensors at the concentrations encountered in the buildings, which were normally less than 500 ppm during the testing. For analyses, these data were combined with data from the calibration challenges at 510 ppm obtained during the multi-concentration calibration checks. For the resulting data set, the average error was 60 ppm and the average of the absolute value of error was 154 ppm.

Statistical analyses indicated that there were statistically significant differences between the average accuracies of sensors from different manufacturers. Sensors with a “single lamp single wavelength” design tended to have a statistically significantly smaller average error than sensors with other designs except for “single lamp dual wavelength” sensors, which did not have a statistically significantly lower accuracy. Sensor age was not consistently a statistically significant predictor of error.

Errors based on the CO_2 concentrations displayed by building energy management systems were generally very close to the errors determined from sensor displays (when available). The average of the absolute value of the difference between 113 paired estimates of error was 25 ppm; however, excluding data from two sensors located within the same building, the average

difference was 10 ppm. These findings indicate that the substantial measurement errors found in this study are sensor errors, not errors in translating the sensor output signals to the energy management systems.

Laboratory-based evaluations of nine sensors with large measurement errors did not identify definite causes of sensor failures. The study did determine that four of the nine sensors had an output signal that was essentially invariable with CO_2 concentration; i.e., the sensors were non-functional yet still deployed. The evaluations did identify slight soiling or corrosion of optical cells and, in two sensors, holes in the fabrics through which CO_2 diffuses into optical cells that may possibly have contributed to performance degradations. In one of two cases when the manufacturer's calibration protocol could be implemented, sensor accuracy was clearly improved after the protocol was implemented.

The Iowa Energy Center recently released the results from a laboratory-based study of the accuracy of 15 models of new single-location CO_2 sensors. Although their report does not provide summary statistics, their findings are broadly consistent with the findings of the field studies of CO_2 sensor accuracy described in this report. Many of the new CO_2 sensors had errors greater than 75 ppm and errors greater than 200 ppm were not unusual.

In 13 buildings, the facility manager provided data on the CO_2 set point concentration above which the demand controlled ventilation system increased the rate of ventilation. The reported set point concentrations ranged from 500 ppm (one instance) to 1100 ppm. The building-weighted-average set point concentration was 860 ppm. When asked, no facility manager indicated that they had calibrated sensors since sensor installation.

In a pilot study of the accuracy of multi-location CO_2 measurement systems, data were collected from systems installed in two buildings. The same manufacturer provided the multi-location measurement systems used in both buildings. In the first building, for the range of CO_2 concentrations of key interest, the average and standard deviation in error in the indoor minus outdoor CO_2 concentration difference were 14 ppm and 39 ppm, respectively, and in 16 of 18 cases the error was 36 ppm or smaller. In the second building, the measured CO_2 concentrations were consistently approximately 110 ppm greater than the CO_2 concentration measured with the reference CO_2 instrument. Outdoor CO_2 concentrations measured by the building's measurement system averaged approximately 510 ppm which is approximately 110 ppm larger than the typical outdoor air CO_2 concentration. In both of these buildings, the error in the difference between indoor and outdoor CO_2 concentration, which is the appropriate control input for demand controlled ventilation, was small except at a couple measurement locations.

The purpose of the multi-point measurements of CO_2 concentrations in occupied meeting rooms was to provide information for selecting sensor installation locations. Data were analyzed for 30 to 90 minute periods of meeting room occupancy. The Title 24 standard requires that CO_2 be measured between 0.9 and 1.8 m (3 and 6 ft) above the floor. The results of the multi-point measurements varied among the meeting rooms. In some instances, concentrations at different wall-mounted sample points varied by more than 200 ppm and concentrations at these locations sometimes fluctuated rapidly. These concentration differences may be a consequence, in part, of the high concentrations of CO_2 (e.g., 50,000 ppm) in the exhaled breath of nearby occupants. In

four of seven data sets, the period-average CO_2 concentration at return grilles were within 5% of the period-average of all CO_2 concentration measurements made at locations on walls; for the other three data sets the deviations were 7, 11, and 16%. Return-air CO_2 concentrations were not consistently higher or lower than the average concentration at locations on walls. In four data sets, the period-average return-air CO_2 concentration was between the lowest and highest period-average concentration measured at wall locations, while in the other three data sets the period average concentrations were lowest at the return grilles. There was no consistent increase or decrease in CO_2 concentrations with height.

Together, the findings from the laboratory studies of the Iowa Energy Center and the current field studies described in this report indicate that many CO_2 based demand controlled ventilation systems will, because of poor sensor accuracy, fail to meet the design goals of saving energy while assuring that ventilation rates meet code requirements. Given this situation, one must question whether the current prescriptions for demand controlled ventilation in the Title 24 standard are adequate. However, given the importance of ventilation and the energy savings potential of demand controlled ventilation, technology improvement activities by industry as well as further research are warranted. Some possible technical options for improving the performance of demand controlled ventilation are listed below:

- Manufacturers of single-location CO_2 sensors for demand controlled ventilation applications change technologies to improve CO_2 sensor accuracy. Sensor costs are likely to increase.
- Users of CO_2 sensors for demand controlled ventilation applications perform sensor calibrations immediately after initial sensor installation and periodically thereafter. Research is needed to determine if such a protocol would lead to acceptable accuracy and whether costs are acceptable.
- Demand controlled ventilation systems employ existing CO_2 sensors that are more accurate, stable, and expensive than the sensors traditionally used for demand controlled ventilation. To spread the cost of these sensors, multi-location sampling systems may be necessary. The pilot scale evaluations of this option included in this project are too limited for conclusions but suggest that these systems may be more accurate. System costs will need to be reduced.
- Demand controlled ventilation systems utilize sensors that count occupants, as opposed to sensors that measure CO_2 concentrations.

With respect to selecting locations for CO_2 sensors in meeting rooms, this research does not result in definitive guidance; however, the results suggest that measurements at return-air grilles may be preferred to measurements at wall-mounted locations.

INTRODUCTION

People produce and exhale carbon dioxide (CO_2) as a consequence of their normal metabolic processes; thus, the concentrations of CO_2 inside occupied buildings are higher than the concentrations of CO_2 in the outdoor air. The magnitude of the indoor-outdoor concentration difference decreases as the building's ventilation rate per person increases. If the building has a nearly constant occupancy for several hours and the ventilation rate is nearly constant, the

ventilation rate per person can be estimated from the maximum steady state difference between indoor and outdoor CO_2 concentrations (Persily 1997; ASTM 1998). For example, under steady conditions, if the indoor CO_2 concentration in an office work environment is 700 parts per million above the outdoor concentration, the ventilation rate is approximately 7.5 L/s (15 cfm) per person (ASHRAE 2007). In many real buildings, occupancy and ventilation rates are not stable for sufficient periods to allow indoor CO_2 concentrations to equilibrate sufficiently for accurate determinations of ventilation rates from CO_2 data; however, CO_2 concentrations remain an approximate, easily measured, and widely used proxy for ventilation rate per occupant. The difference between the indoor and outdoor CO_2 concentration is also a proxy for the indoor concentrations of other occupant-generated bioeffluents, such as body odors (Persily 1997).

Epidemiological research has found that indoor CO_2 concentrations are useful in predicting human health and performance. Many studies have found that occupants of office buildings with a higher difference between indoor and outdoor CO_2 concentration have, on average, increased sick building syndrome health symptoms (Seppanen et al. 1999). In a study within a jail, higher CO_2 concentrations were associated with increased respiratory disease (Hoge et al. 1994) and higher CO_2 concentrations in schools have been associated with increased student absence (Shendell et al. 2004) and office worker absence (Milton et al. 2000). Additionally, a recent study (Shaughnessy et al. 2006) found poorer student performance on standardized academic performance tests correlated with increased CO_2 in classrooms and Wargocki and Wyon (Wargocki and Wyon 2007) found that students performed various school-work tasks less rapidly when the classroom CO_2 concentration was higher.

In a control strategy called demand controlled ventilation (Fisk and de Almeida 1998; Emmerich and Persily 2001), CO_2 sensors, sometimes called CO_2 transmitters, are deployed in commercial buildings to obtain CO_2 data that are used to automatically modulate rates of outdoor air supply. The goal is to keep ventilation rates at or above design requirements but also to adjust the outside air supply rate with changes in occupancy in order to save energy by avoiding over-ventilation relative to design requirements. Demand controlled ventilation is most often used in spaces such as meeting rooms with variable and sometimes dense occupancy. Some buildings use CO_2 sensors just to provide feedback about ventilation rates to the building operator, without automatic modulation of ventilation rates based on the measured CO_2 concentrations. In nearly all cases, each of the CO_2 sensors deployed for demand controlled ventilation measure CO_2 concentrations at a single indoor location. In this report, these sensors are referred to as "single-location" CO_2 sensors. A small number of buildings utilize CO_2 sensors connected to tubing, valves, and pumps for measurements of CO_2 concentrations as multiple indoor locations as well as outdoors. In this report, these systems are referred to as "multi-location" CO_2 measurement systems.

Reviews of the research literature on demand controlled ventilation (Fisk and de Almeida 1998; Emmerich and Persily 2001; Apte 2006) indicate a significant potential for energy savings, particularly in buildings or spaces with a high and variable occupancy. Based on modeling (Brandemuehl and Braun 1999), cooling energy savings from applications of demand controlled ventilation are as high as 20%. However, there have been many anecdotal reports of poor CO_2 sensor performance in actual applications of demand controlled ventilation. Also, pilot studies

of sensor accuracy in California buildings indicated substantial error in the measures made by many of the evaluated CO_2 sensors (Fisk et al. 2007).

Based on the prior discussion, there is a good justification for monitoring indoor CO_2 concentrations and using these concentrations to modulate rates of outdoor air supply. However, this strategy will only be effective if CO_2 sensors have a reasonable accuracy in practice.

This report provides the results of subtasks 2.1 through 2.3 within a broader research project. Subtask 2.1 is entitled "Field studies of CO_2 sensor performance". The goals were to evaluate the in-situ accuracy of CO_2 sensors used for CO_2 demand controlled ventilation and, to the degree possible via analyses of the data, to determine how accuracy varies with sensor age and sensor technical features; b) to evaluate requirements for CO_2 sensor installation locations. The primary effort in Subtask 2.1 was an evaluation of the accuracy of a large sample of single-location CO_2 sensors, i.e., sensors used to measure CO_2 concentrations at single indoor locations in commercial buildings within California. In general, large commercial buildings with DCV deploy several of these single-location sensors at different indoor locations, e.g., within meeting rooms, general office spaces, or return air ducts that draw air from these spaces. An element of Subtask 2.1 investigated how CO_2 concentrations varied spatially in meeting rooms suitable for demand controlled ventilation. The purpose was to provide information for guidance on the selection of sensor installation locations.

Subtask 2.2 was an evaluation of a selection of single-location CO_2 sensors that had large errors, with the goal of identifying causes of sensor inaccuracy.

Subtask 2.3 is entitled "Pilot evaluation of CO_2 DVC with multi-location[1] sampling systems." The goal of this subtask was to provide an initial indication of the potential of CO_2 monitoring using more expensive, and thus potentially more stable and accurate, CO_2 sensors coupled with multi-location sampling systems. Systems that employ multi-location sampling equipment to measure CO_2 concentrations at multiple locations using the same CO_2 sensor are used much less common than distributed single-location sensors. Multi-location systems have advantages and disadvantages. Advantages include the use of one sensor to measure at multiple locations potentially reducing total sensor costs, the potential to spend more to obtain a higher quality sensor if it is used for multiple-location measurements, the ease of calibrating a single or small number of sensors relative to calibrating many sensors, and the potential to include an outdoor CO_2 measurement in each building, or preferably, with each CO_2 sensor. Also, the multi-location sampling system may, in some cases, be usable to measure contaminants other than CO_2. Disadvantages include the need for a multi-location sampling systems of tubing, valves, and pumps, the potential for leakage-related errors with multi-location sampling, the need for a sample pump, and the reduced frequency in which CO_2 concentration data are available from each location.

[1] For clarity the subtask title was changed slightly from that in the research proposal.

METHODS

Subtask 2.1 Field studies of single-location CO_2 sensor performance

The research on single-location CO_2 sensors, hereinafter called "sensors," was performed in two phases. The pilot study phase supported by the U.S. Department of Energy evaluated the performance of 43 CO_2 sensors located in nine buildings in California. The second study phase supported by the California Energy Commission evaluated the performance of 165 sensors from 25 buildings in California. This report presents and analyzes the data from both study phases, with a total of 208 sensors located in 34 buildings. Two different protocols were employed to assess the accuracy of the CO_2 sensors. When possible, bags of primary standard CO_2 calibration gases were used to evaluate sensor performance at five CO_2 concentrations from 230 to 1780 parts per million (ppm). This procedure is referred to as a multi-concentration calibration check. Based on the specifications of the calibration gas supplier and the protocols employed, the calibration gas concentrations were known within about 5%. In the multi-concentration calibration checks, the CO_2 sensors located in buildings sampled each of the calibration gas mixtures. The CO_2 concentrations reported on the computer screen of the building's data acquisition system or on the CO_2 sensor display, or when possible at both locations, were recorded. The data obtained were processed to obtain a zero offset error and slope or sensor gain error using a least-squares linear regression of measured CO_2 concentration versus "true" reference CO_2 concentration. If a sensor agreed exactly with the "true" concentration, then the zero offset error would be zero and the slope equal unity. However, an offset error of 50 ppm would indicate that the sensor would read 50 ppm high at a concentration of 0 ppm, and 50 ppm high at all CO_2 concentrations if the sensor's slope is unity. A slope of 0.8 would indicate that slope of the line of reported concentration plotted versus true concentration is 0.8. The multi-concentration calibration process also yielded errors at each of the calibration gas concentrations. The three calibration gas concentrations used that are most representative of the CO_2 concentrations typically encountered in buildings are 510, 760, and 1010 ppm. The multi-concentration calibrations were performed when the CO_2 sensors had an inlet port and the sensor had a concentration display or the building operator was able and willing to program the data acquisition system so that data were provided with sufficient frequency (e.g., every several minutes) to make a multipoint calibration possible with calibration gas bags of a practical volume. This type of performance test was completed for 90 sensors from 19 buildings.

When a multi-concentration calibration check was not possible, single-concentration calibration checks of the building's CO_2 sensors were performed using a co-located and calibrated reference CO_2 instrument. The protocol was very simple. A calibrated research-grade CO_2 instrument was taken to the building where its calibration was checked with samples of primary standard calibration gases. The reference instrument was placed so that it sampled at the same location as the building's CO_2 sensor. Data from the reference instrument was logged over time. CO_2 concentrations reported on the sensor's display or the building's data acquisition system's screen, or at both locations, were recorded manually. The data were processed to obtain an absolute error, equal to the CO_2 concentration reported by the building's data acquisition system minus the true CO_2 concentration. This type of sensor performance check was completed for 118

sensors located in 24 buildings, including single-concentration calibration checks of sensors for which multi-concentration calibrations were also completed. One limitation of the single-concentration calibration data is that much of the data were obtained with CO_2 concentrations below 500 ppm, with an average concentration of 466 ppm. For subsequent analyses, the data from the single-concentration calibration checks was combined with the data obtained using the 510 ppm calibration gas in the multi-concentration calibration checks of sensors. When both types of data were available, the data obtained with the 510 ppm calibration gas was used in analyses. The resulting data set is called the "combined dataset" and contained data from 207 sensors in 34 buildings[2].

The reference CO_2 instrument used for the single point calibrations has an automatic zero feature and is calibrated with a span gas. The rated accuracy is "better than 1% of span concentration" but is limited by the accuracy of the calibration gas mixture. In this study, the span gas concentration was 2536 ppm and rated at ± 2% accuracy. Multi-concentration calibration checks of this reference instrument were also performed using precision dilutions of the span gas during field site visits. Figure 1 shows an example of the deviations between the reference instrument output and the concentration of CO_2 in the diluted span gas. The deviations range from approximately +1% to – 2%. To further evaluate the accuracy of measurements with the reference instrument, it was used to measure the CO_2 concentration in nine additional calibration gas mixtures, all distinct from the span gas routinely used for instrument calibration checks. As shown in Figure 2, the reference instrument output deviated from the reported calibration gas concentration by approximately -1% to -5%. Given these data, the uncertainty in CO_2 concentration measurements made with the reference instrument is estimated to be 5% or less.

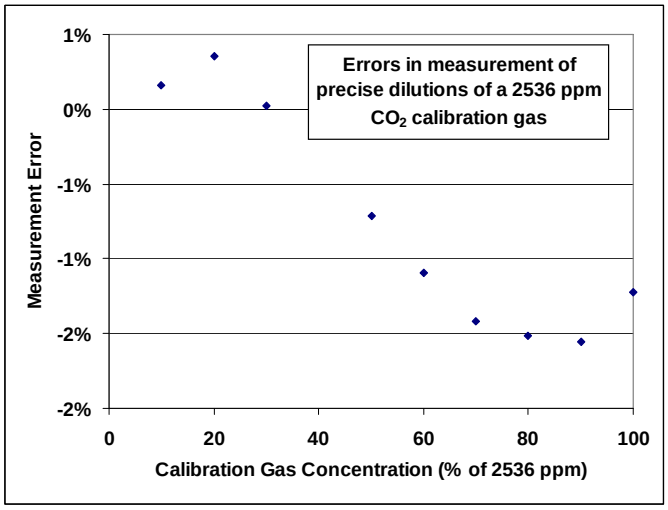

Figure 1 Example of measurement errors of reference CO_2 instrument when measuring precise dilutions of the span gas.

[2] One of the multipoint sensor calibrations lacked data at 510 ppm for combination with the single point data.

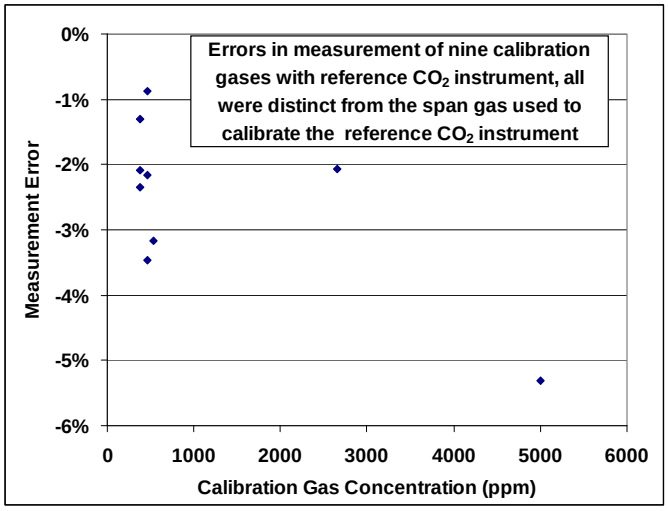

Figure 2 Errors in measuring the concentration of nine CO_2 calibration gases with the reference CO_2 instrument.

All of the CO_2 sensors evaluated were non dispersive infrared sensors. The sensors generally have a default measurement range of zero to 2000 ppm, although in some cases other ranges can be selected. Nearly all sensors sampled via diffusion, i.e., had no sample pump. The manufacturers' accuracy specifications translate into maximum errors of ± 40 ppm to ± 100 ppm at a concentration of 1000 ppm if the sensor range is zero to 2000 ppm. The manufacturers' recommended calibration frequency ranged from every six to 12 months for older products to "never needs a calibration under normal conditions," with a five year recommended calibration interval being common. Some sensors use two lamps or two wavelengths of infrared energy in a process to correct for sources of potential drift in sensor calibration, e.g., to correct for diminished lamp infrared energy output (National Buildings Controls Information Program 2009). For analysis purposes, sensors were classified into the following four design categories: single lamp, single wavelength; dual lamp, single wavelength; single lamp, dual wavelength; or unknown when product literature did not specify the design. In this classification scheme, "lamp" refers to the infrared source(s) and "wavelength" refers to the wavelength(s) of infrared energy detected by the sensor's detector. Based on product literature, some sensors perform a self-calibration or auto-calibration. In many instances, this self calibration is an "automated background calibration" process in which the sensor's calibration is automatically reset based on a complex algorithm and the lowest sensor responses encountered during a prior period. This automatic background calibration process assumes that the lowest encountered CO_2 concentration is approximately 400 ppm; i.e., that the CO_2 concentration at the sensor location drops to the outdoor air CO_2 concentration. However, product literature for some sensors simply refers to a "self calibration" without providing details, and for many sensors the product literature does not indicate whether or not there is a self calibration feature.

For analyses of how various sensor features related with sensor accuracy, sensors were assigned a manufacturer code number (1 – 10 plus 11 for a few sensors locked in a box with an unknown manufacturer), a sensor design code, a self calibration code, and a sensor age. Sensors were

assigned the sensor design code based on a review of product literature. The sensor design code numbers and corresponding sensor designs were as follows: 1 = known single lamp single wavelength; 2 = suspected single lamp single wavelength; 3 = dual lamp single wavelength; 4 = single lamp dual wavelength; 5 = unknown. For many sensors, the sensor design code could not be determined due to, for example, the lack of design information on product literature. Sensors were also grouped into the following two categories: sensors in which product literature refers to a self-calibration feature (normally automatic baseline control) and other sensors. This categorization is crude. The designs of dual lamp and dual wavelength sensors are intended to automatically correct for sources of error which could be considered a form of self-calibration, but normally the product literature for these sensors did not refer to a self-calibration.

Facility managers were asked about the sensor age; i.e., the time elapsed since sensor installation in the building, the CO_2 concentration setpoint used to trigger an increase in ventilation rate, the sensor calibration history, and the sensor cost. In general they provided only estimates of sensor ages, some did not know the setpoint, and almost none provided any specific information on costs. No facility manager reported that they had calibrated the sensors since their initial installation in the building. For analysis purposes, an age of 0.5 years was assigned for sensors characterized by the facility manager as "new." When a facility manager indicated that a sensor was more than "n" years old, "n" was assigned as the sensor age.

Bivariate statistical analyses were performed using the anova and regress commands in STATA version 10. For the multi-concentration calibration checks, outcomes were the absolute value of error at 760 and 1010 ppm. For the combined single-concentration and multi-concentration calibration data, the outcome was absolute error at the concentration encountered or at 510 ppm. Outcome variables were log-transformed to produce normally-distributed residuals with a constant variance, as is required for valid inference from ANOVA and linear regression models. Groups with fewer than 11 observations were excluded from the analysis. Pairwise comparisons of groups were performed using the Tukey wholly significant difference method with α=0.05. This method makes it more difficult to reject the null hypothesis in each individual pairwise comparison. Additionally, sensor types were analyzed using both the individual types (1-5) and groupings of type 1 and 2 versus types 3, 4, and 5. Sensor age was treated as a categorical variable with groups 0-1 year, 1.5-3 years, 3.5-5 years, and 5-7 years for the combined dataset and groups 0-1 year, 1.5-3 years, and 3.5-7 years for the multi-concentration dataset. Linear regression was performed on the log-transformed year, using the robust standard errors option.

Multivariate statistical analyses were performed using the regress command with the robust standard error option specified for both the combined dataset and the multi-concentration dataset on its own. All outcomes (absolute error, absolute error at 760 ppm, absolute error at 1010 ppm) were log-transformed in order to meet the assumptions for regression. A dummy variable was created for each sensor grouping category with categories containing very few observations combined into an "other" category. Sensor age was introduced as a categorical measure with categories defined as in the bivariate analysis.

The sensor performance checks, for single-location sensors, were all performed in commercial buildings located in California, selected without consideration of building age or type of CO_2 sensor. The buildings were used for healthcare, education, software industry, judicial, library,

utility, corrections, law enforcement, museum, entertainment, retail, and state and federal and private office applications. There were ten brands of CO_2 sensors[3] and multiple model types of some brands.

In addition to the field studies of the accuracy of single-location CO_2 sensors, subtask 2.1 included multipoint measurements of CO_2 concentrations in six meeting spaces suitable for demand controlled ventilation. Concentrations of CO_2 were measured once per minute at various locations and heights on meeting room walls and in return air grilles. Figure 3 shows a schematic of one of three measurement systems, each with the capability for measurements at three locations. Samples were drawn continuously from each sample point. Sequential activation of the three-way solenoid valves for a 20 second periods directed air from specific sample points to the CO_2 instrument, which is the same type of instrument described above as the reference CO_2 instrument. When a solenoid valve was not activated, the sample stream was vented. The continuous sampling through the sample inlet tubes maintained the tubes purged so that data could be collected at high frequency. The system was calibrated using bags of primary standard calibration gas mixtures attached at the inlet end of the sample lines. The output of the CO_2 instrument was logged continuously and reported every two seconds. Approximately 10 - 12 seconds after activation of a solenoid valve, the output signal from the CO_2 instrument was stable if the concentration at the inlet line of the sample tube was stable, indicating purging of the sample hardware downstream of the three-way valve and equilibration of the instrument response. The output signal from the subsequent sample period was converted to the CO_2 concentration using the calibration data for the CO_2 instrument. The system was tested before use and the CO_2 instrument was calibrated at each installation location.

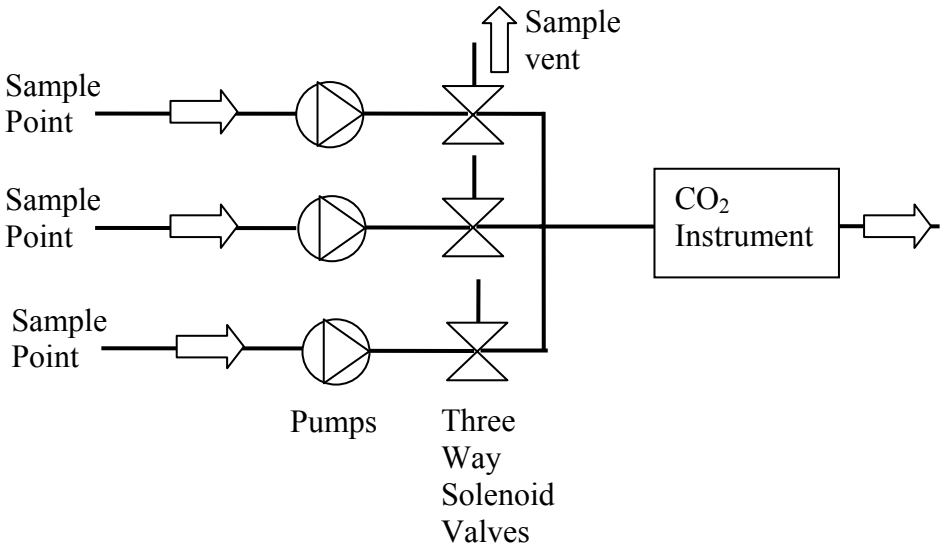

Figure 3 Schematic representation of one of three systems employed to rapidly measure indoor carbon dioxide concentrations at three indoor locations per system.

[3] Some of the manufacturers market sensors from other manufacturers.

The three systems provided measurements at nine locations. In general, the measurement locations included a location on each wall at approximately a 1.5 m (5.0 ft) above the floor (typical of the heights at which sensors were installed in field settings), inside one or two return grilles, at lower and higher heights (typically 0.4 and 1.7 m or 1.5 and 5.5 ft) at one of the walls, and a supply air register. In some spaces, the measurement heights had to be adjusted to accommodate wall mounted equipment, such as white boards or display screens. Based on the data, one of the supply airstreams may have contained only recirculated room air. In one meeting room, many chairs were placed immediately adjacent to parts of some walls and sample locations were selected away from these chairs to reduce the impacts of exhaled air with very high CO_2 concentrations.

Subtask 2.2. Evaluation of faulty single-location CO_2 sensors.

Nine of the single-location CO_2 sensors that had large measurement errors (range 255 – 858 ppm, average 458 ppm) based on the assessments performed for Subtask 2.1 were obtained for further evaluation in the laboratory. To obtain the sensors, facility managers were offered a new replacement sensor if they would provide a specified existing sensor for evaluation. In the prior field studies, these sensors had received only a single-concentration calibration check using a co-located and calibrated reference CO_2 instrument. Sensors from four different manufacturers and with different design features were obtained. The following evaluation protocol was implemented.

The first step in the evaluation was designed to evaluate the sensor responses at multiple CO_2 concentrations after 11 days of sensor operation in a highly ventilated room with outdoor air CO_2 concentrations. After this conditioning period, during which "automated background calibration" software may have corrected some of the sensor calibrations, CO_2 concentrations in the room were normally equal to the outdoor air concentration. Periodically, pure CO_2 was added to room air in amounts sufficient to increase concentrations to approximately 500, 700, 1000, and 1500 ppm and the air in the room was mixed using fans. A reference CO_2 instrument continuously monitored CO_2 concentrations within the room. The output signal of the sensors was logged continuously. The resulting data were analyzed to determine measurement errors and whether they were stable.

The second step was to implement the manufacturer's recommended sensor calibration protocols when possible and then to reassess sensor performance using the protocols described in the previous paragraph. For two sensors, the manufacturer provided no calibration protocol. Four sensors had no response or only a very small response to changing CO_2 concentrations. One sensor had an output signal problem that caused the data acquisition system to fail. Thus, a manufacturer's recommended calibration could only be implemented for two sensors. For one of these sensors, the manufacturer's protocol utilized only a calibration gas with no CO_2. For the other sensor, the manufacturer's protocol utilized both a 0 ppm CO_2 calibration gas and a 2000 ppm CO_2 calibration gas.

The third evaluation step was to remove the sensor covers and have an electronics expert inspect each sensor for visual evidence of any electronics component failures. Based on a discussion with the research director of a sensor company and an examination of the limited technical information available from sensor manufacturers it was determined that detailed studies of the electronic performance of sensors was not feasible. Measurement of the output of the IR lamps was also not feasible as no lamp output data or evaluation protocols were available and most sensor lamps were inside optical cells that could not be opened non-destructively.

In the final step in the evaluations, the optical cells of each sensor were opened and the cells visually inspected under low power magnification for signs of soiling or corrosion of the cell surfaces.

Subtask 2.3. Pilot evaluation of CO_2 demand controlled ventilation with multi-location sampling systems

For subtask 2.3, the accuracy of multi-location CO_2 measurement systems was evaluated in two buildings. The same manufacturer provided the multi-location systems used in both buildings. There are two additional manufacturers of multi-location CO_2 measurement systems, but one has only a few installations and was not able to provide convenient access for our studies and the second was identified after data collection took place.

The two multi-location CO_2 measurement systems that were evaluated employ tubing, valves, and a pump to draw air from multiple indoor locations to the same sensor. In one building, three measurement systems, each with its own CO_2 sensor, are employed to measure at 45 locations. In the second building, one system is used to measure CO_2 at 27 locations. The tubing is a carbon "nanotube and fluoropolomer blend" designed to transport particles and some other contaminants (e.g., volatile organic compounds) without losses to the tubing walls. No evaluations were performed of the performance of the tubing relative to these design goals. Special tubing is not critical for transporting CO_2, as CO_2 is a highly volatile and relatively unreactive gas much less subject to depositional losses on tubing walls than particles and many volatile organic compounds. In each building, the outdoor-air CO_2 concentrations as well as the indoor CO_2 concentration at multiple locations are measured. The ventilation control algorithms are based on the difference between indoor and outdoor CO_2 concentrations. Consequently, sensor offset errors can cancel out, e.g., if a system measured both the indoor and outdoor CO_2 concentration as 100 ppm greater than the true concentration, there would be no error in the difference between indoor and outdoor concentration. This manufacturer offers a sensor exchange service in which approximately every six months, the manufacturer sends the user recently-calibrated CO_2 sensors and the user returns their previously-used sensors to the manufacturer for calibration.

The evaluation protocols were very similar to the protocols described above for single-location sensors. In one building, the systems were challenged with multiple bags of calibration gases that have known CO_2 concentrations. The bags were attached to sample inlet points for three-to-

four measurement cycles. In this building, and in the second building, co-located calibrated reference CO_2 instruments were also employed to evaluate measurement accuracy.

When multi-concentration calibrations were performed, large volumes of calibration gas mixtures were necessary because of the large sample flow rates of the building's CO_2 measurement systems – initially 20 L/min after switching to a new sample location. It was impractical to transport (via commercial aircraft) multiple bags with sufficiently large volumes of the calibration gas mixtures to the study site. Consequently, bags of calibration gas mixtures were prepared on site by mixing indoor air and a small amount of pure CO_2 in a gas sample bag. The concentrations of CO_2 in the resulting sample bags were determined on-site with the calibrated reference CO_2 analyzer before and after the bags were used to check the response of the building's CO_2 measurement systems. The multi-concentration calibration protocol was developed in consultation with the manufacturer of the multi-location CO_2 measurement system to assure purging of sample lines and instrumentation with the calibration gas samples.

The facility managers for the buildings with the multi-location CO_2 measurement systems were asked the date of installation, the reason for selecting the system, the initial system cost (no initial cost data were supplied directly by facility managers), the CO_2 setpoint, the calibration practices and costs, how the CO_2 data were utilized, and about their experience with the system. Because facility managers did not provide cost data, estimates of installed costs were obtained from the manufacturer.

RESULTS

Subtask 2.1 Field studies of CO_2 sensor performance

Multi-concentration calibration checks of single-location sensors

Table 1 provides the primary results from the multi-concentration calibration checks of 90 sensors. The first row of data provides the results of evaluations of all 90 sensors and subsequent rows provide results for overlapping subsets of the sensors. Data from each sensor is provided in Appendix 1. For the full set of sensors, the average slope was 0.97 and the average of the absolute value of zero offsets was 79 ppm. The averages of the absolute values of error were 118 ppm (16%) and 138 ppm (14%), at concentrations of 760 and 1010 ppm, respectively. The calibration data are generally well fit by a straight line as indicated by the high values of R^2. For subsets of the full set of sensors, the accuracy is often significantly better or worse than for the full set of sensors. For example, sensors from Manufacturer 4 and 5, sensors with the Type 1 design (single lamp and single wavelength) or with Type 2 design (suspected single lamp and single wavelength design), and sensors with a manufacturer-reported self-calibration system tend to have a better-than-average average accuracy. However, the variability in sensor accuracy within each category is large, as indicated by standard deviations that are often comparable to or larger than the average error for the category.

Figure 4 provides frequency distributions for the slope, zero offset, error at 760 ppm, and error at 1010 ppm that clearly illustrate the high variability in accuracy. In each case the error parameters are approximately normally distributed. Figure 5 shows how error at the 760 and 1010 ppm concentration varies with manufacturer code and the figure provides the average absolute value of error for each category. Sensors from Manufacturers 4 and 5 have substantially lower average absolute value errors at 1010 ppm, and sensors from Manufacturer 2 also have the lowest average absolute value error at 760 ppm. Figure 6 shows that the lowest average absolute value errors are associated with sensor design type 1 (single lamp single wavelength) and, at 1010 ppm, also with sensor design type 2 (suspected single lamp single wavelength design). There is a substantial overlap in the sensors within these categories associated with better accuracy; i.e., the sensors from manufacturers 4 and 5 generally had a single lamp single wavelength design and their literature refers to a self-calibration procedure.

As illustrated by the frequency distribution plots in Figure 4, a significant fraction of sensors had errors substantially larger than 100 ppm. For example, at 1010 ppm, 19% of sensors had an error greater than 200 ppm and13% of sensors had errors greater than 300 ppm.

Error is plotted versus sensor age in Figure 7. Given the large standard deviations, indicated by the error bars, there is no clear trend in error with sensor age in the multi-concentration calibration data.

Table 2 provides the proportion of sensors in various categories that had errors greater than ±75 ppm and greater than ±100 ppm at calibration gas concentrations of 760 and 1010 ppm. For the full set of sensors subject to the multi-concentration calibration checks, at 1010 ppm, 40% and 31% of sensors had errors greater than ±75 ppm and ±100 ppm, respectively. At 760 ppm, 47% of sensors had errors greater than ±75 ppm and 37% of sensors had errors greater than ±100 ppm. These proportions varied substantially with manufacturer, sensor design type, and with versus without a self-calibration procedure. Sensors with type 1 (single lamp single wavelength) and type 2 (suspected single lamp single wavelength) designs and those with a self-calibration performed best at 1010 ppm with 12% to 14% having an error greater than ±100 ppm and just over 20% having an error exceeding ±75 ppm. However, at 760 ppm, 36% to 48% of these same sensors had errors exceeding the same criteria.

Table 1 Primary results of the multi-concentration calibration checks of 90 sensors.

Sensor Group	No. of. Sen-sors	Slope		Linearity R^2		Zero Offset		Error at 760 ppm		Error at 1010 ppm		ABV (Zero Offset)		ABV (Error at 760 ppm)		ABV (Error at 1010 ppm)	
		Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg	SD
		----	----	----	----	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
all sensors	90	0.97	0.28	0.97	0.10	14	113	-26	200	-9	258	79	83	118	163	138	218
Manu. 1	4	0.71	0.48	0.79	0.42	-9	36	-235	360	-324	478	27	21	247	349	342	461
Manu. 2	2	0.35	0.08	0.72	0.06	-95	26	-737	27	-774	38	95	26	737	27	774	38
Manu. 4	29	0.91	0.12	0.99	0.02	66	98	1	72	-21	98	88	78	49	52	69	72
Manu. 5	33	0.97	0.09	0.99	0.02	12	84	-37	131	-4	124	59	60	100	91	70	102
Manu. 6	5	1.01	0.21	1.00	0.00	43	26	51	174	61	239	43	26	93	151	134	198
Manu. 7	16	1.19	0.49	0.98	0.03	-67	166	64	252	153	385	124	127	179	184	281	299
Type 1	26	0.95	0.06	1.00	0.00	30	76	16	71	10	80	64	49	49	53	53	59
Type 2	17	0.98	0.06	0.98	0.01	-28	45	-126	35	-45	53	45	26	126	35	49	49
Type 3	2	0.41	0.59	0.57	0.59	-25	43	-476	396	-650	507	30	35	476	396	650	507
Type 4	27	1.06	0.42	0.98	0.03	1	168	34	198	68	318	116	120	125	156	204	250
Type 5	18	0.90	0.25	0.97	0.09	57	95	-32	296	-48	325	80	75	156	250	190	265
No Self-Cal.	39	0.99	0.42	0.95	0.15	8	152	-17	288	1	386	101	112	176	226	250	291
Self-Cal.	51	0.95	0.07	0.99	0.01	19	73	-34	88	-17	72	62	43	73	58	53	52
Age 0 - 1 yr	26	1.09	0.43	0.98	0.03	7	166	81	181	121	307	109	123	119	157	204	258
Age 1.5 - 3 yr	23	0.98	0.06	0.98	0.02	-15	47	-91	69	-32	55	42	25	99	55	46	44
Age 3.5 - 7 yr	37	0.94	0.10	1.00	0.00	45	94	2	132	-11	149	82	65	75	108	88	120

Key: ABV = absolute value, Avg = average, Cal. = calibration, Manu = manufacturer, SD = standard deviation, Type 1 is single lamp single wavelength, Type 2 is suspected single lamp single wavelength, Type 3 is dual lamp single wavelength; Type 4 is single lamp dual wavelength; Type 5 = unknown type

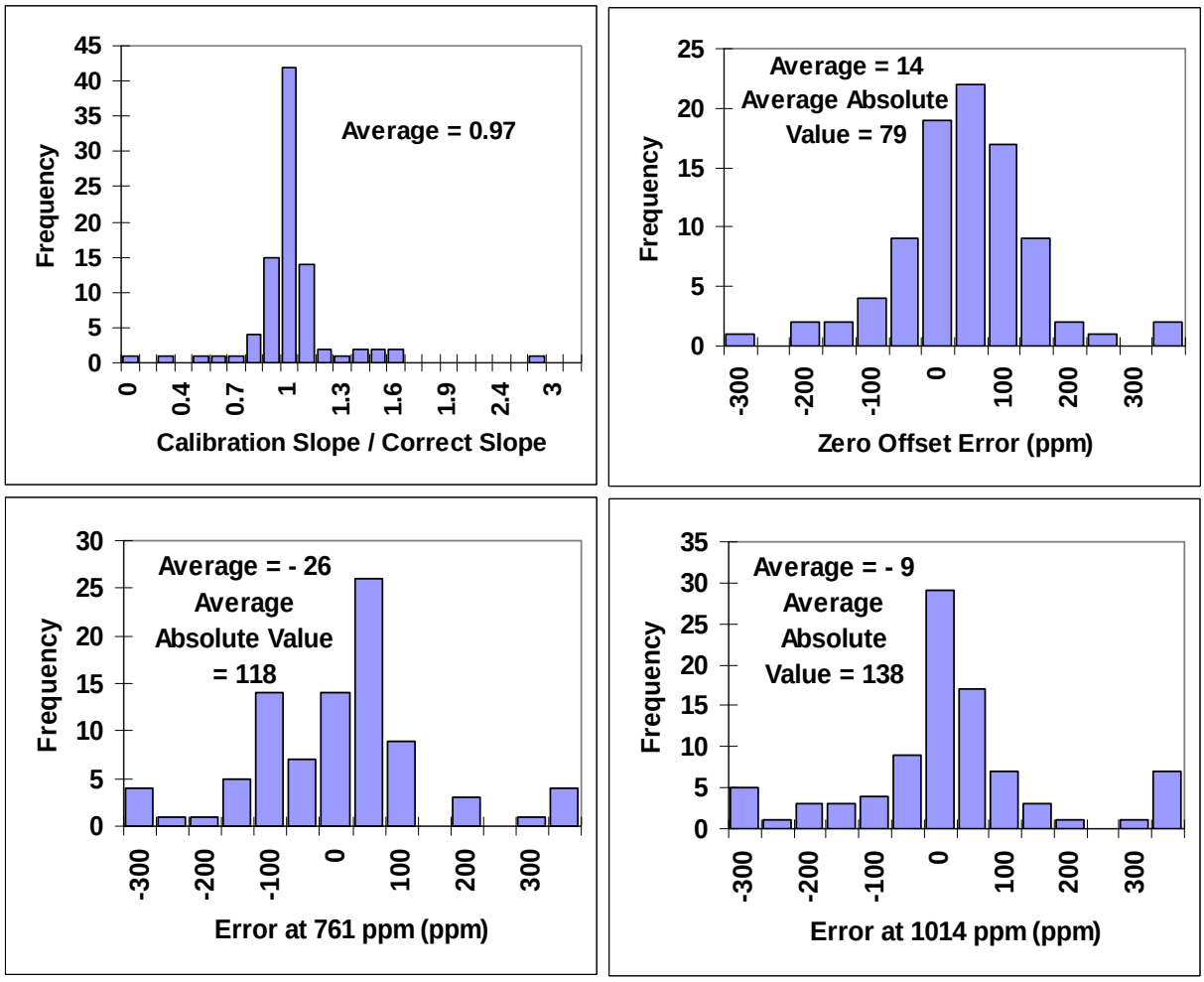

Figure 4 Frequency distributions of key results from the multi-concentration calibration checks.

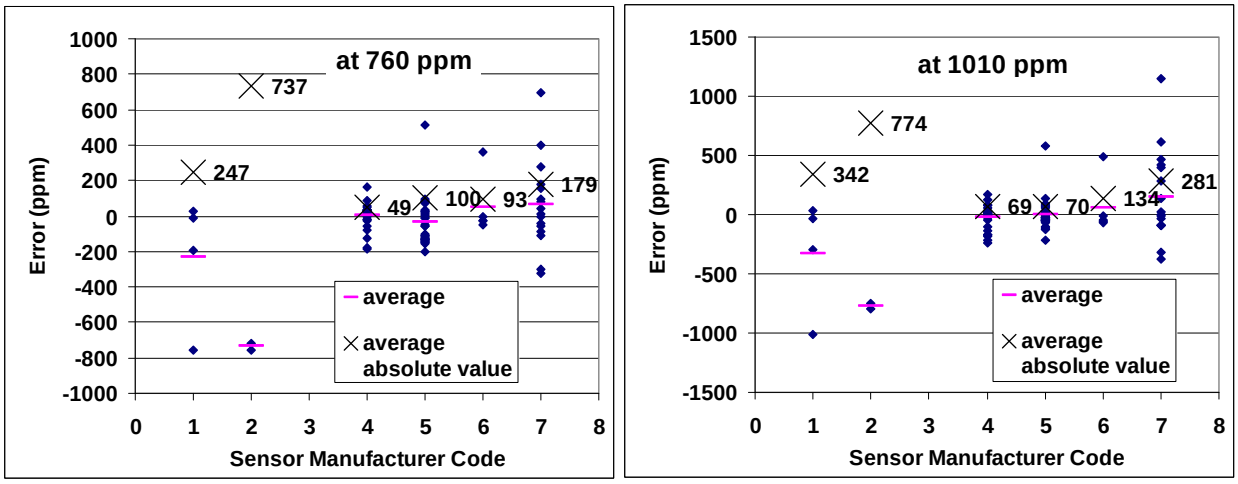

Figure 5 Errors at 760 and 1010 ppm versus manufacturer code from multi-concentration calibration checks.

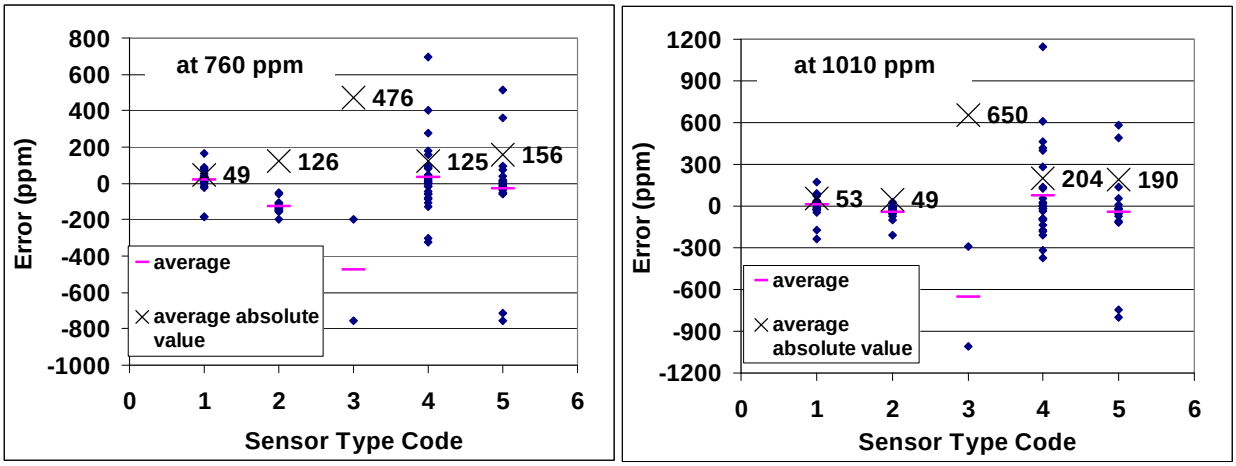

Figure 6 Errors at 760 and 1010 ppm versus sensor design type from multi-concentration calibration checks.

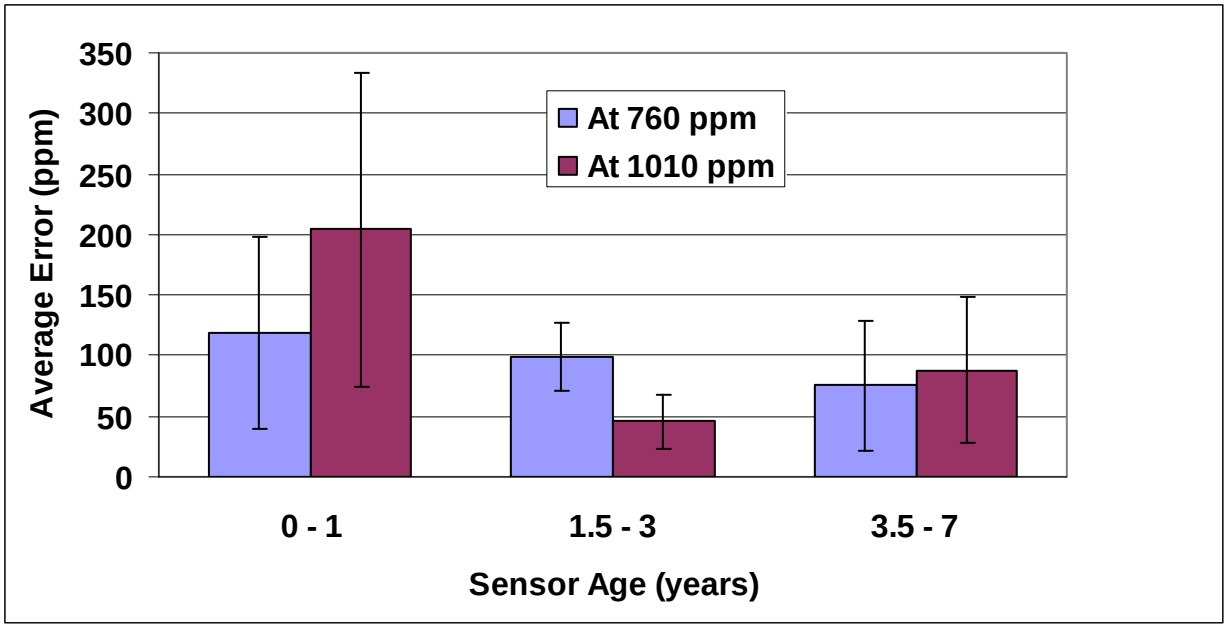

Figure 7 Errors at 760 and 1010 ppm versus sensor age from multi-concentration calibration checks. The error bars represent one standard deviation in the error.

Table 2 Proportions of CO_2 sensors in various sensor categories with errors greater than ±75 and ±100 ppm in the multi-concentration calibration checks.

Sensor Group	No. of Sensors	At 760 ppm		At 1010 ppm	
		Proportion with error > ±75 ppm	Proportion with error > ±100ppm	Proportion with error > ±75 ppm	Proportion with error > ± 100ppm
all sensors	90	0.47	0.37	0.40	0.31
Manu. 1	4	0.50	0.50	0.50	0.50
Manu. 2	2	1.00	1.00	1.00	1.00
Manu. 4	29	0.21	0.14	0.37	0.27
Manu. 5	33	0.61	0.48	0.24	0.18
Manu. 6	5	0.20	0.20	0.20	0.20
Manu. 7	16	0.69	0.50	0.75	0.56
Type 1	26	0.20	0.12	0.27	0.12
Type 2	17	0.88	0.88	0.12	0.12
Type 3	2	1.00	1.00	1.00	1.00
Type 4	27	0.52	0.33	0.67	0.52
Type 5	18	1.00	0.22	1.00	0.39
Type 1 - 2	43	0.48	0.43	0.21	0.12
Type 3 - 5	47	0.47	0.32	0.57	0.49
No Self-Cal.	39	0.54	0.38	0.64	0.54
Self-Cal.	51	0.42	0.36	0.22	0.14

Manu = manufacturer; Cal = calibration, Type 1 is single lamp single wavelength, Type 2 is suspected single lamp single wavelength, Type 3 is dual lamp single wavelength; Type 4 is single lamp dual wavelength; Type 5 = unknown type

Combined Dataset

Table 3 provides the primary results of data from the single-concentration calibration checks combined with the data from challenging sensors with a 510 ppm calibration gas in the multi-concentration calibration checks. Data for individual sensors are provided in Appendix 1. For the full set of 207 sensors, the average error was 60 ppm and the average of the absolute value of error was 154 ppm. The standard deviations associated with these two averages were high, 263 and 222 ppm, respectively. Considering only categories with greater than 10 sensors, average absolute value of error was smallest for Manufacturer 5 (58 ppm) and for sensor design types 1 and 2 (66 and 24 ppm, respectively). Again, sensors with a self-calibration designated in product literature had a lower average absolute value error (83 versus 218 ppm). The average of absolute value of error increased with sensor age. However, the standard deviations in the errors in each category were generally larger than the average errors.

Table 3 Primary results of the single-concentration calibration checks and multi-concentration calibration challenges at 510 ppm.

		Error		Average Absolute Value of Error			
Sensor Group	No of. Sensors	Average (ppm)	Standard Deviation (ppm)	Average (ppm)	Standard Deviation (ppm)	Proportion > 75 ppm	Proportion > 100 ppm
All sensors	207	60	263	154	222	0.43	0.36
Manu 1	13	-110	250	206	172	0.77	0.77
Manu 2	2	-504	2	504	2	1.00	1.00
Manu 3	19	278	359	364	190	0.84	0.74
Manu 4	57	35	261	125	231	0.35	0.28
Manu 5	49	38	100	58	90	0.16	0.12
Manu 6	5	37	117	62	104	0.20	0.20
Manu 7	22	-60	329	177	281	0.50	0.41
Manu 8	14	269	278	271	276	0.79	0.57
Manu 9	6	66	48	66	48	0.33	0.33
Manu 10	3	18	67	45	45	0.33	0.00
Manu 11	17	151	177	159	170	0.41	0.35
Type 1	48	32	96	66	76	0.27	0.17
Type 2	22	16	28	24	22	0.05	0.00
Type 3	11	-131	268	243	161	0.91	0.91
Type 4	34	-23	269	131	235	0.41	0.32
Type 5	92	138	322	228	265	0.55	0.49
Types 1 and 2	70	27	81	53	67	0.20	0.11
Types 3 - 5	137	76	317	205	253	0.55	0.48
No Self-Calibration	109	56	335	218	260	0.57	0.51
With Self-Calibration	98	64	150	83	140	0.28	0.18
Age 0 - 1 yr	46	51	114	80	95	0.35	0.26
Age 1.5 - 3 yr	47	87	201	109	190	0.34	0.21
Age 3.5 - 5 yr	66	79	284	165	244	0.37	0.31
Age 5 - 7 yr	35	46	371	244	287	0.66	0.63

Manu = manufacturer; Type 1 is single lamp single wavelength, Type 2 is suspected single lamp single wavelength, Type 3 is dual lamp single wavelength; Type 4 is single lamp dual wavelength; Type 5 = unknown type

Figure 8 shows the roughly normal frequency distribution of errors and Figure 9 shows errors plotted versus sensor manufacturer and sensor design type. These figures illustrate the large variability of error within each category of sensors.

Average and standard deviation of error is plotted versus sensor age in Figure 10. There is a trend toward higher absolute value of error with increased sensor age; however, the standard deviations in error for each age category are large.

The proportions of all 207 sensors with absolute values of error exceeding 75 ppm and 100 ppm were 43% and 36%, respectively (Table 3). These proportions varied substantially among the overlapping subcategories of sensors. These high errors were found in smaller proportions of sensors from Manufacturers 5 and 6, with design types 1 and 2, and with a manufacturer-specified self calibration procedure.

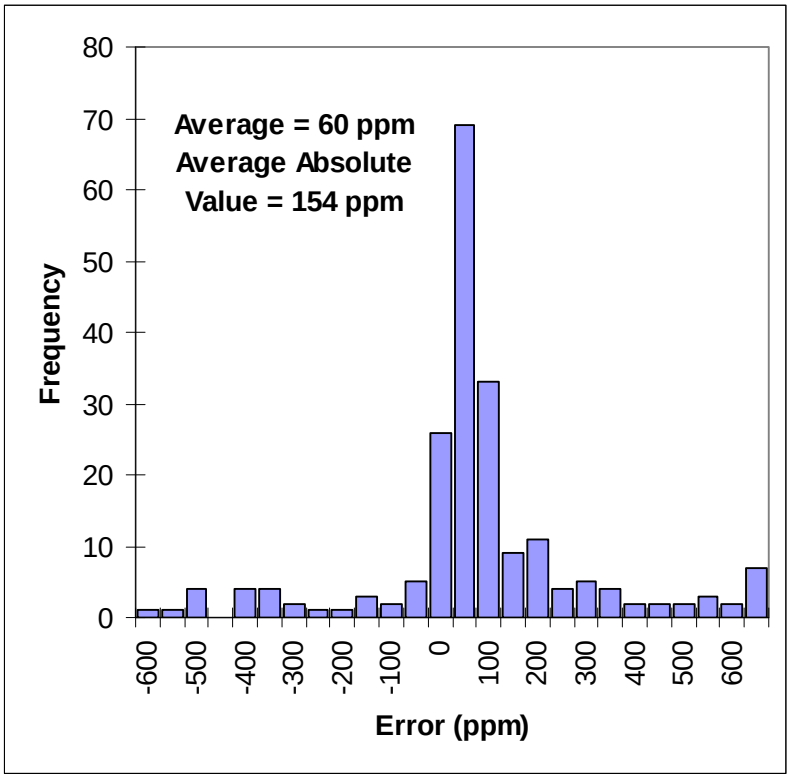

Figure 8 Frequency distribution of error from single-concentration calibration checks and multi-concentration calibration challenges at 510 ppm

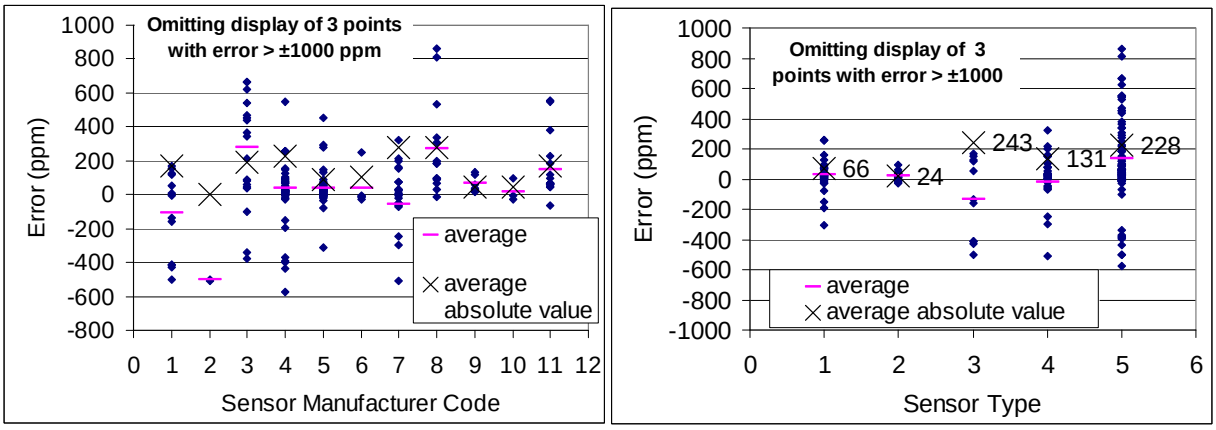

Figure 9 Error from single-concentration calibration checks and multi-concentration calibration challenges at 510 ppm plotted versus manufacturer and sensor design type.

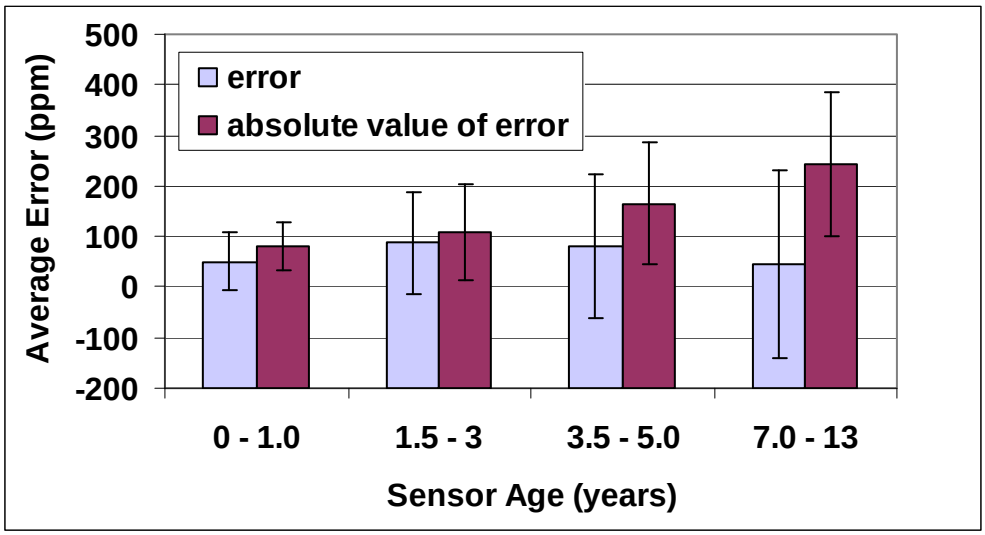

Figure 10 Error from single-concentration calibration checks and multi-concentration calibration challenges at 510 ppm plotted versus sensor age. The error bars represent one standard deviation in the error.

Carbon dioxide concentration setpoints

In only 13 of 25 buildings within the California Energy Commission-supported studies, did the facility manager provide data on the indoor CO_2 set point concentration above which the demand controlled ventilation system increased the rate of ventilation. (Asking facility managers for setpoint concentrations was not part of the protocol in the initial pilot study supported by the U.S. Department of Energy.) Within eleven of these buildings, the same setpoint concentration was reported for all sensors. The reported set point concentrations ranged from 500 ppm (one instance) to 1100 ppm. The building-weighted average set point concentration was 860 ppm, if one uses for this calculation the sensor-weighted averages for buildings with multiple set point concentrations. The most frequently reported set point concentration was 800 ppm, which was reported for all sensors in 4 buildings and also reported for some sensors in two additional buildings.

Repeatability of errors

Multi-concentration calibration checks were repeated for four sensors. In every case, the resulting slope differed by 0.01 or less. The zero offsets differed by 16 ppm or less, with an average deviation of 8 ppm. The error at the 1010 ppm challenge concentration repeated within 16 ppm or less with an average deviation of 9 ppm.

Single-concentration calibration checks were repeated for five sensors. For three sensors the resulting error repeated within 18 ppm or less. For one sensor the error in the repeat test was 113

ppm larger than the error in the initial test. For the fifth sensor, the single-concentration check was repeated twice when the investigators noticed a large discrepancy and suspected a possible procedural error. The first repetition yielded an error 60 ppm different than the first test while the error in the second repetition was only 9 ppm different from that in the first repetition.

Errors from energy management systems versus sensor displays

Because the main objective of this research was to evaluate sensor accuracy, primary analyses relied on data from sensor displays whenever available. However, for 38 sensors in six buildings, all where multi-concentration calibration checks were performed, data were collected from both the sensor display and the energy management system's computer display. The errors at the 510, 760, and 1010 ppm challenges of the 38 sensors yielded 113 instances in which errors based on data from energy management systems could be compared to errors based on sensor displays. The average of the absolute value of the difference between the paired estimates of error was 25 ppm; however, excluding data from two sensors located within the same building, the average difference was 10 ppm. For the two sensors in which data from the energy management system and sensor display differed dramatically, the average absolute value difference was 290 ppm. For at least one of these sensors, it was clear that the energy management system's data was not from the correct sensor. In general; however, these findings indicate that the substantial measurement errors found in this study are sensor errors, not errors in translating the sensor output signals to the energy management systems.

Statistical significance of differences in sensor accuracy

Table 4 lists the results of the statistical analyses of sensor errors. The table lists paired categories of sensors for which the average absolute value errors were statistically significantly different, i.e., 95% confidence intervals excluded unity. In bivariate analyses, sensors from Manufacturer 4 (and to a more limited extent from Manufacturer 5) tended to have significantly smaller errors than errors from most of the other manufacturers. Also, sensor type 1 (single lamp single wavelength) sensors tended to have smaller errors than other sensor types except type 4 (single lamp dual wavelength). In some cases, sensors with a reported self-calibration had statistically significantly smaller errors than sensors without a reported self-calibration. In general, error was not significantly associated with sensor age. Many of the differences found to be statistically significant in bivariate analyses remained significant in the multivariate analyses, except self-calibration was no longer a significant predictor of error, presumably because self-calibration is correlated with sensor manufacturer and sensor type which are better predictors of error. The multivariate analyses identified a few statistically significant differences in average errors that were not evident in the bivariate analyses, possibly because the bivariate analysis method is slightly more conservative.

Table 4 Differences in averages of absolute value errors that were statistically significant (p<0.05)*

		Analyses	
Dataset	**Category**	**Bivariate**	**Multivariate**
Multi-Concen-tration Calibration Challenge, 760 ppm	Manufacturer	Error (M4) < Error (M5, M7)	Error(M4) < Error(M7)
	Sensor Type	Error(T1) < Error(T2)	Error(T1) < Error(T2) Error (T5) < Error(T2)
	Self-Calibration	---	---
	Sensor Age	---	---
Multi-Concen-tration Calibration Challenge, 1010 ppm	Manufacturer	Error(M4) < Error(M7) Error(M5) < Error(M7)	---
	Sensor Type	Error(T1+T2) < Error(T3+T4+T5)	---
	Self-Calibration	Error(with SC) < Error(without SC)	---
	Sensor Age	---	---
Combined	Manufacturer	Error(M4) < Error(M3, M8) Error(M5) < Error(M3, M7, M8) Error(M7) < Error(M3)	Error(M1) < Error(M4) Error(M4) < Error(M3, M7, M8) Error(M5) < Error(M3, M8)
	Sensor Type	Error(T1) < Error(T3, T5) Error(T2) < Error(T3, T5) Error(T4) < Error(T3) Error(T1+T2) < Error(T3+T4+T5)	Error(T1) < Error(T3) Error(T2) < Error(T3) Error(T4) < Error(T3) Error(T5) < Error(T3)
	Self-Calibration	Error(with SC) < Error(without SC)	---
	Sensor Age	Error(Age 0–1 yrs) < Error(Age 5–7 yrs)	Error(Age 3.5–5 yrs) < Error(Age 5–7 yrs)

*Subcategories are indicated by the following symbols: M1 – M8 = manufacturer 1 – manufacturer 8; T1 – T5 = sensor type 1 – sensor type 5, where T1 is single lamp single wavelength, T2 is suspected single lamp single wavelength, T3 is dual lamp single wavelength; T4 is single lamp dual wavelength; T5 = unknown. SC = self calibration

Spatial variability of CO_2 concentration in meeting rooms

Figure 11 provides an example plot of the results of multipoint monitoring of carbon dioxide concentrations during a noon-time seminar in a crowded 76 m^2 conference room. In this instance, the CO_2 concentrations, varied among locations at any one time by up to approximately 300 ppm, and fluctuated substantially with time at many locations. Concentrations at return grilles were in the middle of the range. The concentration at the west wall location may be lowest because the people were not located close to this location which was directly below the screen used for display of presentations. Concentrations measured at the 0.3 m height on the east wall are moderately lower than concentrations measured at the 1.4 and 1.8 m heights.

In three of six meeting rooms, concentrations fluctuated rapidly as illustrated in Figure 11, potentially, in part, because of the CO_2 in exhaled breath from people near sample points. During measurements in meeting rooms 1 and 4, it is known that the rooms were very crowded with people sitting or standing near sample locations. The CO_2 concentrations measured by the sensors used for demand controlled ventilation applications will most likely vary less, as these sensors sample diffusively and respond more slowly than the instruments used in this research. In the remaining three meeting rooms, concentration fluctuations, as illustrated in Figure 12, were less pronounced.

Data similar to those illustrated in Figures 11 and 12 were collected from seven total time periods in six meeting rooms. Table 5 provides information on the meeting rooms and measured CO_2 concentrations. From each data set, period-average (i.e., time-average over the selected time period) CO_2 concentrations are provided at each measurement location for periods of 30 to 90 minutes when concentrations were elevated above background due to occupancy of the meeting room. For the example datasets shown in Figure 11 and 12, concentrations were averaged for the 12:15 to 13:00 and 14:10 to 14:55 time periods, respectively. The range in period-average CO_2 concentrations at the wall mounted sample points located in the same meeting room varied from 43 to 242 ppm. In four of seven data sets, the period-average CO_2 concentration at return grilles were within 5% of the period average of all CO_2 concentration measurements made at locations on walls, for the other three data sets the deviations were 7, 11, and 16%. Return-air CO_2 concentrations were not consistently higher or lower than the average concentration at locations on walls. In four data sets, the period-average return-air CO_2 concentration was between the lowest and highest period-average concentration measured at wall locations, while in the other three data sets the period average concentrations were lowest at the return grilles. There was no consistent increase or decrease in CO_2 concentrations with height at the three co-linear Wall-4 measurement locations, and the concentrations at different walls often varied more than concentrations varied with height at Wall 4. In the four instances with CO_2 measurements at two return-air grilles, the associated two period-average CO_2 concentrations differed by 6 ppm or less.

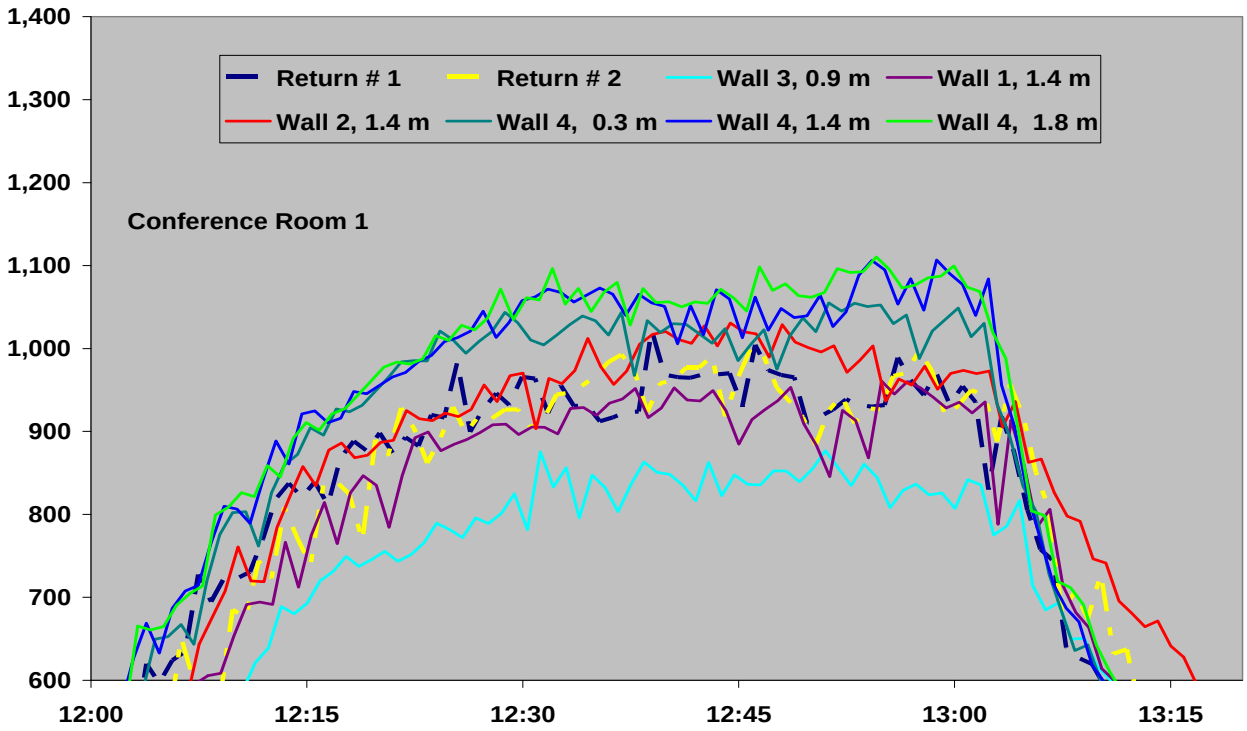

Figure 11 First example of data from studies of spatial distributions of CO_2 concentrations in occupied meeting rooms.

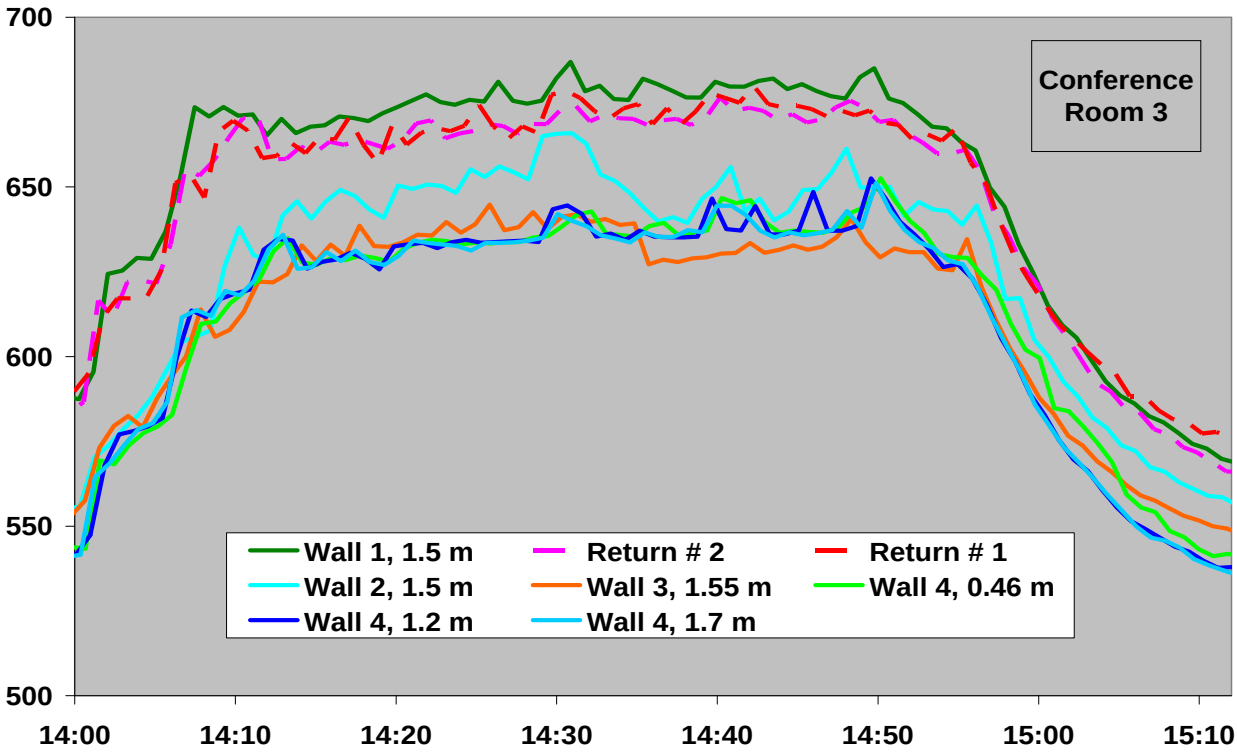

Figure 12 Second example of data from studies of spatial distributions of CO_2 concentrations in occupied meeting rooms.

Table 5 Spatial variability of CO_2 concentrations in occupied meeting rooms. The numbers are averages and standard deviations for 30 – 90 minute meetings, unless indicated otherwise.

Conf, Room	1	2	3	3	4	5	6
Floor Area (m^2)	76	45	59	59	160	115	46
Ceiling Height (m)	2.7	2.7	2.8	2.8	2.7 – 4.7	3.0	3.0
CO_2 Concentration (standard deviation) in ppm or Concentration Ratio							
Wall 1	902 (48)	722 (23)	675 (5)	626 (23)	1,668 (185)	943 (145)	640 (68)
Wall 2	960 (51)	724 (32)	648 (8)	599 (16)	1,774 (166)	909 (160)	515 (43)
Wall 3	811 (45)	719 (34)	632 (7)	594 (17)	1,910 (263)	964 (137)	562 (58)
Wall 4 Low	1007 (39)	708 (22)	635 (7)	582 (19)	1,672 (238)	903 (100)	533 (49)
Wall 4 medium	1029 (51)	704 (36)	635 (6)	583 (18)	1,734 (232	961 (153)	554 (61)
Wall 4 high	1042 (53)	651 (64)	634 (6)	584 (18)	1,759 (243)	945 (126)	571 (80)
Wall 5	NA	NA	NA	NA	1,823 (277)	967 (177)	621 (74)
All Wall locations	959 (94)	704 (47)	643 (17)	595 (23)	1,754 (247)	940 (146)	571 (75)
All Wall (max – min)*	231	73	43	43	242	64	124
Return Grille 1	931 (43)	593 (30)	669 (5)	616 (16)	NA	NA	NA
Return Grille 2	925 (54)	596 (34)	668 (5)	615 (17)	1,877 (216)	890 (124)	510 (48)
Return Average / All Wall Average	0.97	0.84	1.04	1.03	1.07	0.95	0.89
Supply	433 (6)	451 (18)	613 (5)	581 (14)	1,413 (150)	849 (130)	424 (5)

*maximum minus minimum of average CO_2 concentrations measured at locations on walls
^return grille was mounted in a wall, not in the ceiling of the meeting room

Subtask 2.2. Evaluation of faulty single-location CO_2 sensors

Table 6 provides descriptive information for the faulty single-location CO_2 sensors evaluated in the laboratory and the major findings of the evaluations. These faulty sensors are from four manufacturers, have multiple design types, and are two to 13 years old. Four of the nine sensors had either no output signal or had an output signal that changed little or none as the CO_2 concentration varied. A fifth sensor repeatedly caused the data acquisition system to shut down, thus, it could not be subjected to tests. Measurements showed that the sensor's output voltage was highly erratic and the sensor repeatedly attempted to re-initialize its operation. Thus, five of nine sensors were essentially non-functional, although four of these were approximately 13 years old. Sensor FS4 had stable errors which varied with CO_2 concentration between 240 to 410 ppm before the manufacturer's zero and span gas calibration protocol were implemented; subsequently, its errors were 33 to 76 ppm (Figure 13). Sensor FS5, which had a 310 ppm error in the field setting, had errors of 0 to 95 ppm in the laboratory (after the conditioning period) and these errors did not change significantly after implementing the manufacturer's calibration protocol which involved only use of a zero-CO_2 gas. Sensors FS6 and FS7 had fluctuating errors of five to 158 ppm and 79 to 310 ppm, respectively, during the laboratory studies, which were

much smaller than the approximately 800 ppm errors in the field setting for both of these sensors, which came from the same building. The smaller errors observed in the laboratory studies of Sensors FS5 – FS7, relative to the errors observed for the same sensors in the field studies, might be a consequence of automatic calibration corrections during the 11 days of sensor deployment in the laboratory (if CO_2 concentrations in the field setting were not regularly decreasing to the outdoor CO_2 concentration) and for FS7 the trends suggest further improvements in accuracy (Figure 14). Another possibility is that there were signal processing problems in the field settings. These sensors had no output displays; therefore, the original field studies of the accuracy of these sensors accuracy relied on the CO_2 concentrations reported by energy management systems.

The visual inspection of sensor electronics by an electronics expert indicated no visually obvious electronics failures except in the one sensor with an erratic output voltage that caused the data acquisition system to shut down. In this sensor, an electrical pin that extended out the back of the circuit board and plugged into a socket in the wall mounting plate had a loose pin. This electrical pin became totally disconnected from the circuit board during the inspection process.

The visual inspections of optical cells indicated small amounts of particle deposits or corrosion on the reflective surfaces of the optical cells of six sensors. The amount of deposits or corrosion was never large enough to be a definite source of sensor malfunction. One older non-functional sensor had a window between the optical cell and detector that was partially soiled or discolored. In two sensors, there were one or more small holes, roughly 0.5 mm in diameter, in the fabric covered openings to optical cells. These fabric covered openings provide the path for CO_2 to "diffuse" into the cells while excluding airborne particles.

In summary, these evaluations of faulty sensors did not identify definite causes of sensor failures. The study did determine that four of the nine sensors had an output signal that was essentially invariable with CO_2 concentration and that a fifth sensor had a highly erratic output signal; i.e., the sensors were non-functional, yet still deployed. The evaluations did identify slight soiling or corrosion of optical cells and, in two sensors, holes in the fabrics through which CO_2 diffuses into optical cells which may have contributed to performance degradations. In one of two cases when a manufacturer's calibration protocol could be implemented, sensor accuracy was clearly improved after the protocol was implemented.

Table 6 Properties of faulty sensors evaluated in the laboratory and key findings.

I.D. Code	Man No.*	Sensor Type[#]	Self Calibra-tion	Sensor Age (yr)	Man has Cal[+] Protocol	Summary of Findings	Results of Inspection of Optical Cell
FS1	1	3	--	~ 13	Yes*	very small response to changing CO_2 concentrations	slight soiling of window between cell and detector
FS2	1	3	--	~ 13	Yes*	small response to changing CO_2 concentrations	no evidence of soiling or corrosion
FS3	4	5^	--	~ 13	Yes	no response to changing CO_2 concentrations	hole in fabric covered opening to cell; scattered particle deposits
FS4	4	1	yes	5	Yes	large accuracy improvement after implementing manufacturer's recommended calibration protocol	no evidence of soiling or corrosion
FS5	5	1	yes	2	Yes	fair to good accuracy after 11 days; errors fluctuated up to 60 ppm; accuracy not improved after implementing manufacturer's calibration	soiling or corrosion of cell near lamp
FS6	8	5[#]	yes	3	No	error initially ~ 500 ppm at ~ 1200 ppm, avg. error ~ 50 ppm at 1000 ppm after 11 days, errors fluctuated up to 150 ppm	scattered minor pits or soiling of cell walls
FS7	8	5[+]	yes	3	No	error initially ~ 500 ppm at ~ 1200 ppm, avg. error ~ 60 ppm at 1000 ppm after 11 days, errors fluctuated up to 230 ppm	scattered minor pits or soiling of cell walls
FS8	4	1	yes	~13	Yes	no output signal	multiple holes in fabric covered openings to cell
FS9	4	1	yes	3	Yes	highly erratic output signal caused data acquisition system to shut down,	loose electrical pin (see text), no evidence of soiling or corrosion

*Man = Manufacturer [#]Type 1 is single lamp single wavelength, Type 3 is dual lamp single wavelength; Type 5 = unknown type [+]Cal = Calibration ^single lamp [#] dual lamp
**hardware required for calibration is no longer available

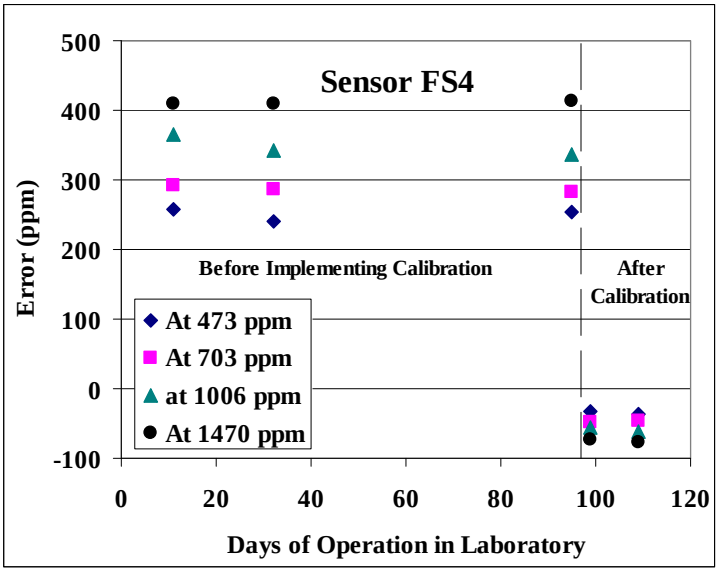

Figure 13 Improvement in accuracy of sensor FS4 after implementing the manufacturer's recommended calibration protocol.

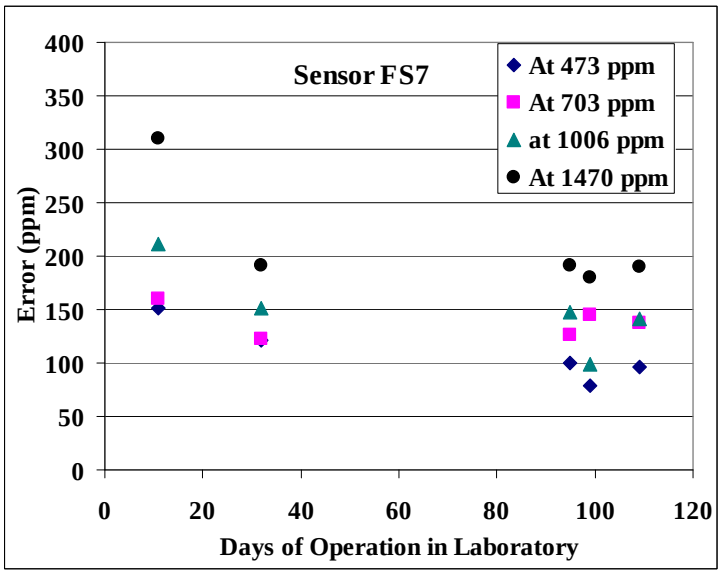

Figure 14 Improvement in accuracy of sensor FS7 during early period of operation in the laboratory.

Subtask 2.3 Pilot evaluation of multi-location CO_2 measurement systems

In Building M1 the challenges with calibration gas mixtures were implemented twice to evaluate three multi-location CO_2 measurement systems. Data from the first implementation of the protocol were judged potentially unreliable because the bags of calibration gases may not have been installed on the sample inlet tubes for a sufficient period; thus, these data have not been utilized. The initial data were reviewed with the manufacturer who, prompted by the test results, evaluated the system and identified and fixed some leaks in the sampling system, prior to the second implementation of the multi-concentration calibration protocol. Thus, the data obtained from studies in Building M1 may not be typical of data for this CO_2 monitoring system. In addition to employing the multi-concentration calibration protocol, the accuracy of CO_2 measurements in Building M1 was also measured using the calibrated reference CO_2 instrument which measured CO_2 concentrations for approximately 30 minute periods at the same locations of the building's multi-location CO_2 measurement systems. Table 7 provides the results from these studies. The average and standard deviation of error in indoor CO_2 concentration when the systems were challenged with calibration gas mixtures with CO_2 concentrations of 525 to 953 ppm was 69 ppm and 40 ppm, respectively. In 13 of 18 cases, the error was less than 25 ppm. For the same concentration range, the average and standard deviation of error in indoor minus outdoor CO_2 concentration difference were 14 ppm and 39 ppm, respectively, and in 16 of 18 cases the error was 36 ppm or smaller. Errors were markedly higher at reference CO_2 concentrations of 1680 and 1844 ppm, but errors in measurements at such high concentrations, which should not occur in buildings with demand controlled ventilation, are not particularly important. Thus, at the concentrations of interest, the indoor-outdoor CO_2 concentration difference, which is the appropriate input to the demand controlled ventilation system, was measured with little error at least at a large majority of the investigated locations.

Figure 15 shows the results of evaluations of the single multi-location CO_2 measurement system in Building M2. The figure compares the concentrations reported by the building's measurement system to the concentrations measured simultaneously with three co-located calibrated reference CO_2 instruments. At all three locations, the building's measurement system utilized the same CO_2 sensor and the measured concentrations were approximately 110 ppm greater than the reference measurements of CO_2 concentration. Outdoor CO_2 concentrations measured by the building's measurement system averaged approximately 510 ppm, which is approximately 110 ppm larger than the typical outdoor air CO_2 concentration. Because the offset error is approximately the same for the indoor and outdoor CO_2 measurements, the error in the difference between indoor and outdoor CO_2 concentration within this building is small. Consequently, as in Building M1 the indoor-outdoor CO_2 concentration difference, which is the appropriate input to the demand controlled ventilation system, was measured with little error at least at the investigated locations.

In both buildings, the multi-location CO_2 monitoring system was installed as part of the process to obtain Leadership in Energy and Environmental Design (LEED certification) and utilized for demand controlled ventilation. Based on a discussion with the facility manager of building M1, the measurement system was one-year old, the CO_2 setpoint was 800 ppm above the outdoor CO_2 concentration, they experienced no problems with the system, and calibrated sensors were provided every six months via a contract with the manufacturer. From discussions with the

facility manager of building M2, the multi-location CO_2 measurement system was 10 months old, calibrated replacement sensors were provided four times per year by the manufacturer, and there had been some commissioning difficulties but no subsequent system problems. No information on the CO_2 setpoint was provided.

Neither facility manager directly provided information on initial system costs, however, the manufacturer estimated that installed costs were typically $1500 to $2500 per sensed location. The system from this manufacturer includes special sampling components that are needed for pollutants other than CO_2, thus, it is not cost optimized for CO_2 – only measurements. The manufacturer's reported cost of calibration services (providing calibrated replacement sensors every six months and replacing sensors when needed), real time sensor diagnostics, warranty, and data services, and was estimated to be $60 to $125 per year per sensed location. For comparison, the cost of traditional demand controlled ventilation with single-location CO_2 sensors used for development of the Title 24 standard is $617 per sensor after adjustment for inflation (Hong and Fisk 2009). However, a $1540 per sensor cost can be derived from a recent cost analyses of obtaining LEED certification (Steven Winters Associates 2004).

Table 7 Results of evaluations of multi-location CO_2 measurement systems in Building M1.

System	Location	Reference CO_2 Concentration (ppm)	Error in Indoor CO_2 Concentration (ppm)	Error in Indoor Minus Outdoor CO_2 Concentration Difference (ppm)
Challenges with calibration gasses				
1	1125	525	80	25
1	3126	525	27	-21
1	3135	525	38	-18
3	1230	569	34	-18
3	2202	569	40	-13
3	2204	569	39	-19
2	4126	570	44	-14
2	5126	570	100	36
2	5163	570	47	-11
3	1230	861	54	-3
3	2202	861	73	22
3	2204	861	64	11
2	4126	867	72	10
2	5126	867	155	98
2	5163	867	78	19
1	1125	953	174	118
1	3126	953	55	0
1	3135	953	73	25
1	1125	1,680	323	276
1	3126	1,680	124	66
1	3135	1,680	131	75
2	4126	1,844	193	133
2	5126	1,844	363	304
2	5163	1,844	200	135
Average and (Standard Deviation) of all results with CO_2 < 1000 ppm			69 (40)	14 (39)
Evaluation with co-located reference CO_2 instrument				
1	2116	427	12	-36
2	5163	543	54	0
2	5163	676	67	11
3	1122	429	31	-24
3	1230	478	36	-23

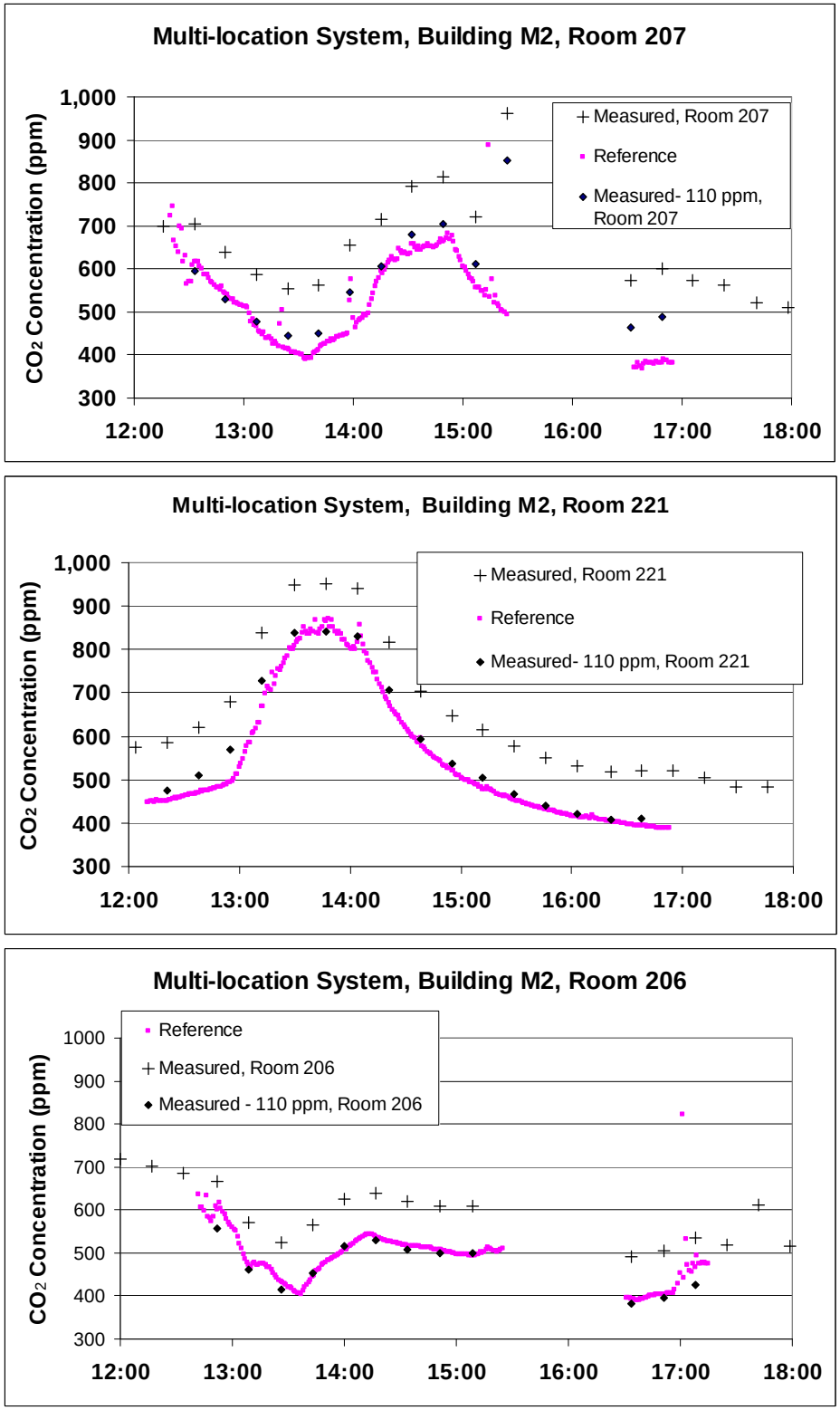

Figure 15 Results of evaluations of the multi-location CO_2 measurement system in building M2.

DISCUSSION

Accuracy requirements

To place the results of this study in context, one must have an estimate of the required accuracy of CO_2 sensors used in commercial buildings for demand controlled ventilation. While most systems only measure the indoor CO_2 concentration, the difference between indoor and outdoor CO_2 concentration is a better indicator of building ventilation rate, and outdoor CO_2 concentrations in urban areas can vary significantly with location and time. One needs to be able to determine with reasonable accuracy the difference between peak indoor and outdoor CO_2 concentrations found in commercial buildings. The most representative data set is that obtained from a survey of 100 office buildings by the U.S. Environmental Protection Agency (EPA). This EPA study measured and recorded five-minute-average CO_2 concentrations at three indoor locations and one outdoor location. If one considers the maximum one-hour average differences between indoor and outdoor CO_2 concentration[4] from this EPA study, the minimum was 55 ppm, maximum was 777 ppm, average was 310 ppm, and median was 269 ppm. If one desires no more than a 20% error in measurements of the average peak indoor-outdoor CO_2 concentration difference, then 62 ppm (one fifth of 310 ppm) is a minimum expectation for CO_2 measurement accuracy in offices. The California Title 24 Standard requires a similar level of accuracy "the CO_2 sensors must be factory certified to have an accuracy of no less than 75 ppm over a five year period without recalibration in the field". Seventy five parts per million corresponds to 16% of the difference between the average set point concentration (860 ppm) reported in this study and the typical outdoor carbon dioxide concentration of 400 ppm.

Accuracy of single-location CO_2 sensors

This study employed two protocols to evaluate sensor error – multi-concentration calibration checks and single-concentration checks. The data from the multi-concentration calibrations, performed whenever possible, have the greatest value because these data yield estimates of sensor accuracy at typical CO_2 setpoint concentrations. The errors at 760 and 1010 ppm may be the most useful indicators of sensor accuracy. The slope and zero offset errors can be counteracting; thus, neither provides a clear indication of overall sensor performance. There is a general consistency among the findings obtained via the two evaluation protocols. The results of both protocols indicate that many sensors had large errors. In general, both protocols indicate that the same subgroups of sensors had superior (or inferior) average performance.

The findings of this research indicate that a substantial fraction of CO_2 sensors had errors greater than specified in Title 24 or provided in the applicable product specifications. Forty seven percent of sensors had errors greater than 75 ppm at a concentration of 760 ppm and 40% of sensors had errors greater than 75 ppm at a concentration of 1010 ppm. A significant fraction of sensors have much larger errors, e.g., > 300 ppm. These concentrations of 760 and 1010 ppm are

[4] Based on authors' analyses of the CO_2 data from this study.

typical of the setpoint concentrations at which demand controlled ventilation systems increase outdoor air ventilation rates. Thus, overall many CO_2 sensors do not meet accuracy requirements

Sensors from specific manufacturers, with a single lamp single wavelength design, and with a self-calibration procedure specified in product literature, had better average accuracy. After multivariate statistical analyses of the data, sensors from some manufacturers had a better average accuracy (particularly Manufacturer 4) and Type 1 sensors (with a single lamp single wavelength design) were generally associated with statistically significantly higher average accuracy. However, use of sensors only in these categories, while helpful, would not result in widespread compliance with the Title 24 accuracy requirements. Twenty one and 37% of sensors from Manufacturer 4 and 20% and 27% of Type 1 sensors still had errors greater than 75 ppm at 760 ppm and 1010 ppm, respectively.

In general, all or most of the sensors within each building were the same model and had the same or a similar age. Thus, sensor manufacturer and sensor type are correlated with the building identification code. In theory, differences in maintenance and calibration practices among buildings might partially explain the observed associations of accuracy with sensor manufacturer and features. However, given that none of the facility managers reported that they had calibrated the sensors in their buildings subsequent to the initial sensor installation, the manufacturer and the sensor design are more likely the real explanation for the observed variability in sensor accuracy.

A significant number of sensors in all age sensor categories had large errors. Thus, replacing sensors every few years also would not solve the accuracy problem.

Because the results obtained from energy management systems generally agreed well with results obtained from sensor displays, the measurement errors appear to be primarily a consequence of sensor problems and not a consequence of errors in translating the sensor output signals to building energy management systems. Having a display on the sensor may, however, be advantageous as it facilitates checks of sensor assignment in the energy management software. Also, periodic visual checks of sensor displays could help facility managers identify obviously faulty sensors.

The analyses of a sample of nine faulty sensors failed to identify definite causes of sensor failures; however, detailed evaluations of the performance of sensor electronics and measurements of the output of infrared sources within sensors were impractical and not implemented. The fact that four of the nine sensors had an output signal that was essentially invariant with CO_2 concentration, yet these sensors were still deployed, indicates that facility managers are not always aware of obviously faulty sensors. These findings suggest that sensor fault detection systems that provide alarms when sensors are clearly faulty (e.g., have invariable outputs) may be beneficial for maintaining performance of demand controlled ventilation systems.

Three of the faulty sensors were 13 years old, the highest sensor age encountered in the study. One might conclude that 13 year old sensors would be expected to be faulty and should have been replaced, although the manufacturer's product literature does not specify a sensor lifetime.

However, if we exclude the data from one outlier with an error of 1486 ppm, the average error of all the 13 year old sensors in the study was the same as the average error of the seven year old sensors. Also, the average error of 7 to 13 year old sensors was not statistically significantly higher than the average age of 3.5 to 5 year old sensors. Thus, the study data provide no clear indication of how long sensors should be deployed.

The Iowa Energy Center (National Buildings Controls Information Program 2009) recently released the results from a laboratory-based study of the accuracy of 15 models of new single-location CO_2 sensors. Although their report does not provide summary statistics, their findings are broadly consistent with the findings of the field studies of CO_2 sensor accuracy described in this report. Many of the new CO_2 sensors had errors greater than 75 ppm, and errors greater than 200 ppm were not unusual. Maximum errors of new sensors approached 500 ppm.

It is important to keep in mind that the reference CO_2 measurements used in this study to evaluate sensor accuracy are imperfect. The linearity of the reference CO_2 instrument, cross comparisons with other instruments, and checks of performance using multiple calibration gases instill confidence in the reference measurements; however, errors of a few percent are still likely. If these errors were systematic, the reported average errors of CO_2 sensors installed in buildings and reported fractions of sensors with large errors could change significantly; however, the main findings and conclusions of this research are not likely to be substantially impacted by errors in the reference CO_2 measurements.

Accuracy of multi-location CO_2 monitoring systems

The data from the pilot studies of the accuracy of multi-location CO_2 monitoring systems are insufficient as a basis for any firm conclusions about the accuracy of these systems; however, the limited results obtained were encouraging. The study results illustrate the advantage of incorporating a measurement of outdoor air CO_2 concentration with each sensor – offset errors cancel out in the indoor minus outdoor CO_2 concentration difference. For widespread acceptance, it seems likely that the costs of these systems will need to be reduced.

Spatial variability of CO_2 concentrations in meeting rooms

The purpose of the multipoint measurements of CO_2 concentrations in occupied meeting rooms was to provide information for locating the CO_2 sensors in meeting rooms. The Title 24 standard requires that CO_2 be measured between 0.9 and 1.8 m (3 and 6 ft) above the floor with no less than one sensor per 930 m^2 of floor area. The results of the multipoint measurements varied among the meeting rooms. In some instances, concentrations at different wall-mounted sample points varied by more than 200 ppm and concentrations at these locations sometimes fluctuated rapidly. These concentration differences may be a consequence, in part, of the high concentrations of CO_2 (e.g., 50,000 ppm) in the exhaled breath of nearby occupants. Because the results of the multipoint measurements varied among meeting rooms, this research does not result in definitive guidance for locating sensors in meeting rooms; however, the results suggest that measurements at return-air grilles may be preferred to measurements at wall-mounted locations. In four out of seven data sets, CO_2 concentration at return-grille locations fell between

the maximum and minimum of CO_2 concentrations at wall-mounted locations and in five of seven data sets, the period average concentration at return grilles was within 10% of the period average concentration measured from sample points on walls.

Overall findings and their implications.

Together, the findings from the laboratory studies of the Iowa Energy Center and current field studies indicate that many CO_2 based demand controlled ventilation systems will fail to meet the design goals of saving energy while assuring that ventilation rates meet code requirements. Given this situation, one must question whether the current prescriptions for demand controlled ventilation in the Title 24 standard are appropriate. However, given the importance of ventilation, and considering the energy savings potential of demand controlled ventilation, technology improvement activities by industry and further research, are warranted. Some possible technical options for improving the performance of demand controlled ventilation are listed below:

- Manufacturers of single-location CO_2 sensors for demand controlled ventilation applications make technology changes that improve CO_2 sensor accuracy. Sensor costs are likely to increase.
- Users of CO_2 sensors for demand controlled ventilation applications perform sensor calibrations immediately after initial sensor installation and periodically thereafter. Research is needed to determine if such a protocol would maintain accuracy and whether costs would be acceptable. At present, such calibrations appear to be very rare as facility managers are continuously facing other demands.
- Demand controlled ventilation systems use existing CO_2 sensors that are more accurate, stable, and expensive than the sensors traditionally used for demand controlled ventilation. To spread the cost of these sensors, multi-location sampling systems may be necessary. Pilot scale evaluations of this option included in this project are too limited for conclusions but suggest that these systems may be more accurate. Costs will likely need to be reduced.
- Demand controlled ventilation systems are controlled by systems that count occupants, as opposed to by systems that measure CO_2 concentrations. Two optical systems for counting occupants as they pass through doorways are being evaluated within this project and the results are presented in another report. Other people-counting options may be feasible, such as radio frequency identification that is now used routinely to indicate location of inventories are provide occupants access through normally locked building doors.

It is clear that further research will be necessary to develop and evaluate these technical options. Policy changes, such as changes in aspects of the Title 24 standard pertaining to demand controlled ventilation, may be an option for stimulating the necessary technology development. A pending task in this research project is to develop a related set of recommendations related to prescriptions for demand controlled ventilation in Title 24.

CONCLUSIONS

The accuracy of single-location CO_2 sensors, as they are applied and maintained for demand controlled ventilation in commercial buildings, is frequently less than specified in the Title 24 standard and frequently less than needed to meet the design goals of saving energy while assuring that ventilation rates meet code requirements.

The average accuracy of single-location CO_2 sensors varies among manufacturers and is higher with a single lamp single wavelength design. However, use of sensors only from the manufacturer with the best average accuracy or only single lamp single wavelength sensors, while helpful, would not result in widespread compliance with the Title 24 sensor accuracy requirements.

Accuracy varied substantially in each age category and, in general, the association of sensor age with accuracy was not statistically significant. Replacing CO_2 sensors every few years would not result in widespread compliance with the Title 24 sensor accuracy requirements.

Because the results obtained from energy management systems generally agreed well with results obtained from sensor displays, the measurement errors of single-location CO_2 sensors appear to be primarily a consequence of sensor problems and not a consequence of errors in translating the sensor output signals to building energy management systems.

No facility manager indicated that they had calibrated the single-location CO_2 sensors in their facility, after the initial sensor installation and checkout period.

The data from the pilot studies of the accuracy of multi-location monitoring systems are insufficient as a basis for firm conclusions about the accuracy of these systems; however, the limited results obtained were encouraging. For widespread acceptance, it seems likely that system costs will need to be reduced.

Because the results of the multipoint CO_2 concentration measurements varied among meeting rooms, this research does not result in definitive guidance for locating sensors in meeting rooms; however, the results suggest that measurements at return-air grilles may be preferred to measurements at wall-mounted locations.

Changes are needed in technologies used for demand controlled ventilation. Research and policy changes may be necessary to stimulate the needed technology improvements.

ACKNOWLEDGMENTS

This work was supported by the California Energy Commission. This research was also supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Program of the U.S. Department of Energy under contract DE-AC02-05CH11231.

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APPENDIX 1. PRIMARY DATA

Table A1. Data from multi-concentration calibration checks of sensor accuracy.

Building	Slope	Zero Offset (ppm)	Linear Fit R^2	Error at 510 ppm (ppm)	Error at 760 ppm (ppm)	Error at 1010 ppm (ppm)	Manufacturer Code	Sensor Type	Self Calibration	Sensor Age (yr))
-1	0.83	-55	0.99	-160	-196	-291	1	3	N	NA
-1	0.40	-113	0.68	-502	-756	-747	2	5	N	NA
-1	0.29	-77	0.76	-505	-717	-800	2	5	N	NA
-1	0.00	6	0.15	-502	-755	-1009	1	3	N	NA
-4	0.96	45	1.00	20	19	1	4	4	N	1
-4	0.93	49	1.00	18	-16	-2	4	4	N	1
-5	1.26	326	1.00	450	513	583	5	5	N	5
-5	1.01	-2	1.00	2	1	13	5	5	N	5
-5	1.14	-19	1.00	41	76	134	5	5	N	5
-6	0.96	31	1.00	10	-3	-11	4	1	Y	2
-6	0.91	45	1.00	7	-26	-44	4	1	Y	2
-6	1.08	-6	1.00	41	54	80	4	1	Y	2
-6	0.95	57	1.00	40	23	16	4	1	Y	2
-7	1.39	81	1.00	247	361	487	6	5	N	1
-7	0.91	39	1.00	-13	-26	-51	6	5	N	1
-8	0.93	21	1.00	-27	-30	-43	6	5	N	1
-9	0.97	18	1.00	-9	-1	-16	6	5	N	1
-9	0.87	56	1.00	-11	-48	-72	6	5	N	1
1	0.71	245	0.98	104	23	-99	4	4	N	0.5
1	0.69	195	0.99	53	-61	-135	4	4	N	0.5
1	0.79	60	0.99	-19	-126	-174	4	4	N	0.5
1	0.85	39	0.97	6	-81	-177	4	4	N	0.5
1	0.51	367	0.89	148	-19	-210	4	4	N	0.5
3	2.66	-534	1.00	319	697	1146	7	4	N	1
3	1.39	105	0.94	213	401	609	7	4	N	1
3	1.44	-119	0.99	152	157	284	7	4	N	1
3	1.50	-136	0.96	-507	180	399	7	4	N	1
3	1.52	-171	0.98	5	277	420	7	4	N	1
3	1.60	-237	0.91		95	467	7	4	N	1
4	0.98	44	1.00	24	38	19	7	4	N	5
4	0.87	38	0.99	-50	-58	-87	7	4	N	5
4	0.92	28	1.00	-22	-41	-38	7	4	N	5
4	0.90	-18	1.00	-64	-107	-91	7	4	N	5
4	0.94	35	1.00	-7	-6	-14	7	4	N	5
4	0.80	-139	1.00	-247	-300	-320	7	4	N	5
4	0.79	-173	1.00	-294	-324	-376	7	4	N	5

Table A1. Data from multi-concentration calibration checks of sensor accuracy (continued)

Build-ing	Slope	Zero Offset (ppm)	Linear Fit R2	Error at 510 ppm (ppm)	Error at 760 ppm (ppm)	Error at 1010 ppm (ppm)	Manu-factur-er Code	Sen-sor Type	Self Cali-bra-tion	Sen-sor Age (yr))
5	1.14	-26	1.00	41	86	126	4	4	N	4
5	1.02	29	1.00	33	47	59	4	4	N	4
5	0.96	57	1.00	31	37	24	4	4	N	4
5	0.95	36	1.00	2	1	-15	4	4	N	4
6	0.88	114	1.00	36	36	28	4	1	Y	3.5
6	0.93	69	1.00	22	25	20	4	1	Y	3.5
6	0.91	97	1.00	38	30	25	4	1	Y	3.5
6	0.84	-68	1.00	-152	-187	-239	4	1	Y	3.5
6	0.93	107	0.99	70	30	83	4	1	Y	3.5
6	0.92	60	1.00	27		-24	4	1	Y	3.5
6	0.92	75	1.00	24	22	18	4	1	Y	3.5
6	0.90	119	1.00	74	36	14	4	1	Y	3.5
6	0.86	105	1.00	24	13	-21	4	1	Y	3.5
6	0.90	75	1.00	19	7	-23	4	1	Y	3.5
6	0.92	74	1.00	18	23	7	4	1	Y	3.5
7	1.01	16	1.00	14	31	39	4	1	Y	7
7	1.06	-226	1.00	-195	-182	-171	4	1	Y	7
7	1.04	119	1.00	126	164	174	4	1	Y	7
7	0.97	32	1.00	19	11	5	4	1	Y	7
16	0.95	-4	0.94	42	-51	-212	5	2	Y	1.5
16	0.81	105	0.98	14	-59	-104	5	2	Y	1.5
17	0.98	-48	0.98	-1	-159	-57	5	2	Y	1.5
17	0.92	39	0.95	92	-151	-27	5	2	Y	1.5
17	0.96	-35	0.95	36	-201	-55	5	2	Y	1.5
17	0.92	3	0.98	-11	-141	-41	5	2	Y	1.5
17	0.93	-18	0.98	-19	-148	-71	5	2	Y	1.5
17	0.98	-21	0.98	19	-121	-47	5	2	Y	1.5
17	1.02	-70	0.99	-5	-134	-40	5	2	Y	1.5
17	1.00	-46	0.98	1	-130	-28	5	2	Y	1.5
17	1.03	-44	0.99	13	-105	-2	5	2	Y	1.5
17	0.99	-65	0.99	-31	-143	-47	5	2	Y	1.5
17	1.02	-60	0.99	0	-126	-9	5	2	Y	1.5
17	1.01	-60	0.99	-4	-125	-35	5	2	Y	1.5
17	1.03	-72	0.99	-8	-133	-19	5	2	Y	1.5
17	1.04	-52	0.98	24	-109	30	5	2	Y	1.5
17	0.99	-28	0.99	11	-112	-2	5	2	Y	1.5

Table A1. Data from multi-concentration calibration checks of sensor accuracy (continued)

Building	Slope	Zero Offset (ppm)	Linear Fit R2	Error at 510 ppm (ppm)	Error at 760 ppm (ppm)	Error at 1010 ppm (ppm)	Manufacturer Code	Sensor Type	Self Calibration	Sensor Age (yr))
21	0.89	59	1.00	21	-9	-111	5	5	Y	4
21	0.83	182	0.99	50	97	56	5	5	Y	4
21	0.89	89	1.00	54	14	-46	5	5	Y	4
21	0.94	64	1.00	31	37	-19	5	5	Y	4
21	0.86	93	1.00	19	-14	-44	5	5	Y	4
21	0.95	39	1.00	6	20	-30	5	5	Y	4
21	0.90	57	1.00	15	-34	-43	5	5	Y	4
21	0.77	110	1.00	-10	-58	-120	5	5	Y	4
23	0.94	30	1.00	-3	-13	-31	1	1	Y	3
23	1.05	-17	1.00	7	24	35	1	1	Y	3
24	0.95	-35	1.00	73	71	78	5	1	Y	1
24	0.95	-26	1.00	41	78	74	5	1	Y	1
24	0.94	-28	1.00	61	87	91	5	1	Y	1
24	0.99	-21	1.00	29	29	21	5	1	Y	1
24	0.99	-19	1.00	25	23	20	5	1	Y	1
25	0.88	16	1.00	-46	-86	-90	7	4	N	1
25	0.97	115	1.00	76	81	133	7	4	N	1
25	0.93	69	1.00	31	11	-3	7	4	N	1

Table A 2. Data from single-concentration calibration checks of sensor performance.

Building	Error (ppm)	Manufacturer Code	Sensor Type	Self Calibration	Sensor Age (yr)
-2	58	3	5	N	4
-2	38	3	5	N	4
-2	341	3	5	N	4
-2	48	3	5	N	4
-2	540	3	5	N	4
-2	-378	3	5	N	4
-2	215	3	5	N	4
-2	-371	4	5	N	NA
-2	662	3	5	N	4
-2	89	3	5	N	4
-2	668	3	5	N	4
-2	1013	3	5	N	4
-2	363	3	5	N	4
-2	-103	3	5	N	4
-2	452	3	5	N	4
-2	621	3	5	N	4
-2	437	3	5	N	4
-2	-342	3	5	N	4
-2	469	3	5	N	4
-2	85	3	5	N	4
-3	292	5	5	N	NA
-3	276	5	5	N	NA
-3	133	5	5	N	NA
-4	78	4	4	N	1
-6	92	4	1	Y	2
2	69	4	1	Y	5
2	156	4	1	Y	5
2	76	4	1	Y	5
2	258	4	1	Y	5
2	1	4	1	Y	5
2	97	4	1	Y	5
2	-20	4	1	Y	5
2	258	4	1	Y	5
2	13	4	1	Y	5
4	-68	7	4	N	5
4	-1298	7	4	N	5
8	65	11	5	N	5
8	64	11	5	N	5
9	59	11	5	N	5
9	61	11	5	N	5
9	47	11	5	N	5
9	57	11	5	N	5
10	64	11	5	N	5
10	68	11	5	N	5

Table A 2. Data from single-concentration calibration checks of sensor performance. (continued).

Building	Error (ppm)	Manufacturer Code	Sensor Type	Self Calibration	Sensor Age (yr)
11	35	5	1	Y	2
11	-310	5	1	Y	2
11	40	5	1	Y	2
11	33	5	1	Y	2
11	-80	5	1	Y	2
11	-1	5	1	Y	2
11	25	5	1	Y	2
12	33	5	2	Y	1
12	26	5	2	Y	1
12	37	5	2	Y	1
12	31	5	2	Y	1
12	65	5	2	Y	1
13	200	7	4	N	1
13	76	7	4	N	1
13	161	7	4	N	1
14	30	8	5	Y	3
14	858	8	5	Y	3
14	67	8	5	Y	3
14	98	8	5	Y	3
14	-14	8	5	Y	3
14	185	8	5	Y	3
14	307	8	5	Y	3
14	530	8	5	Y	3
14	197	8	5	Y	3
14	94	8	5	Y	3
14	86	8	5	Y	3
14	811	8	5	Y	3
14	185	8	5	Y	3
14	336	8	5	Y	3
15	35	9	5	Y	1
15	19	9	5	Y	1
15	30	9	5	Y	1
15	59	9	5	Y	1
15	131	9	5	Y	1
15	119	9	5	Y	1
15	-31	10	1	Y	1
15	-9	10	1	Y	1
18	95	10	1	Y	1
19	-25	4	1	Y	3
19	255	4	1	Y	3

Table A 2. Data from single-concentration calibration checks of sensor performance. (continued).

Building	Error (ppm)	Manufacturer Code	Sensor Type	Self Calibration	Sensor Age (yr)
20	-389	4	5	N	13
20	-415	1	3	N	13
20	-397	4	5	N	13
20	22	4	5	N	13
20	5	4	5	N	13
20	-572	4	5	N	13
20	-429	1	3	N	13
20	-434	4	5	N	13
20	1486	4	5	N	13
20	-413	1	3	N	13
20	10	4	5	N	13
20	-4	4	5	N	13
20	48	4	5	N	13
20	-134	1	3	N	13
20	119	1	3	N	13
20	-9	4	5	N	13
20	51	1	3	N	13
20	154	1	3	N	13
20	25	4	5	N	13
20	168	1	3	N	13
20	551	4	5	N	13
20	124	1	3	N	13
21	151	5	5	N	0.5
22	184	11	5	N	7
22	-67	11	5	N	7
22	552	11	5	N	7
22	45	11	5	N	7
22	545	11	5	N	7
22	116	11	5	N	7
22	226	11	5	N	7
22	378	11	5	N	7
22	97	11	5	N	7
25	10	7	4	N	0.5
25	29	7	4	N	0.5