National Building Controls Information Program

PRODUCT TESTING REPORT

WALL MOUNTED CARBON DIOXIDE (CO_2) TRANSMITTERS

June 2009

TABLE OF CONTENTS

1 Introduction

2 Classification of CO_2 Sensors
- Types of Sensors
- NDIR Sensor Components
- Sensor Configurations

5 Choosing the Right CO_2 Transmitter
- Accuracy
- Operating Range
- Response Time
- Maintenance and Calibration
- Long-term Stability
- CO_2 Transmitter Cost

6 NBCIP Testing
- Manufacturer Information
- Testing Methods

14 NBCIP Test Results
- Accuracy
- Repeatability
- Linearity
- Hysteresis
- Humidity Sensitivity
- Temperature Sensitivity
- Pressure Sensitivity

36 Conclusions
- Next Steps

38 Terms and Definitions

40 Appendices

Program Sponsors

California Energy Commission
Iowa Energy Center

Introduction

Carbon-dioxide (CO_2)[1] transmitters are gaining popularity in building HVAC systems to monitor indoor air CO_2 concentration and to control the outdoor air intake rate. Controlling ventilation air flow rates using CO_2-based Demand Controlled Ventilation (DCV) offers the possibility of reducing the energy penalty associated with over-ventilation during periods of low occupancy, while still ensuring adequate levels of outdoor air ventilation (Emmerich and Persily 2001). A report prepared for DOE (Roth et al. 2005) suggests that DCV can reduce both heating and cooling energy by about 10% or about 0.3 quadrillion BTUs annually.

In CO_2-based DCV systems, the CO_2 level of indoor air is monitored and the outdoor air flow rate is adjusted based on the transmitter output to maintain acceptable CO_2 concentration in the occupied space. The performance of CO_2 transmitters is crucial in this control process. A general guideline often used in DCV is that the CO_2 concentration in a space should not exceed 700 ppm above the ambient CO_2 level. For occupants involved in sedentary activities (such as in an office or classroom) this corresponds to approximately 15 cfm of outdoor air per person. Transmitters which read high will call for more outdoor air resulting in an energy penalty. A transmitter which reads 100 ppm high would result in approximately 17% more ventilation air flow. Transmitters which read low could cause poor indoor air quality. CO_2 transmitters are reported to have technology-specific sensitivities, and unresolved issues including drift, overall accuracy, temperature effect, water vapor, dust buildup, and aging of the light sources etc. (Dougan and Damiano 2004).

Because of their impact on energy usage and indoor air quality, the National Building Controls Information Program (NBCIP) tested and evaluated the performance of Non-Dispersive Infrared (NDIR) wall-mounted CO_2 transmitters used in typical building HVAC applications. NBCIP developed an experimental procedure for testing the CO_2 transmitters, and used this procedure to test fifteen models of CO_2 transmitters.

This NBCIP Product Testing Report provides an overview of factors to consider when purchasing a CO_2 transmitter, presents manufacturer data for transmitters selected for testing, describes the test procedure and test apparatus used by NBCIP to evaluate transmitter performance, and presents test results for accuracy, linearity, hysteresis, repeatability, humidity sensitivity, temperature sensitivity, and pressure sensitivity for each CO_2 transmitter model tested.

[1] *Throughout this report, the CO_2 sensing element is referred to as the sensor. A CO_2 transmitter is a device that consists of a sensor as well as a transducer that converts the sensor reading into an output signal.*

Classification of CO_2 Sensors

The selection of the appropriate carbon dioxide sensor for a particular application requires knowledge of the parameter to be measured, how the sensor works, and its operating characteristics. For a discussion on the fundamentals of measuring carbon dioxide concentrations in air refer to the side bar *Measuring Carbon Dioxide*.

Types of Sensors

Various methods are available for measuring concentrations of CO_2. Each method relies on exploiting one or more physical properties of the gas. Of the various methods, the non-dispersive infrared (NDIR) type is the most common method used in HVAC applications. Other methods (amperometric electrochemical transmitter, potentiometric electrochemical transmitter, colorimetric detector tubes, and mixed-gas transmitter, and photo-acoustic) are described in the 2005 ASHRAE Handbook–*Fundamentals*, and are not discussed here.

NDIR Sensor Components

The essential components of a NDIR CO_2 sensor include one or two IR radiation sources (or lamps), one or more infrared detectors, band pass optical filters, and an optical path between the source and the detector which is open to the air sample. IR sources emit radiation over a broad range of wavelengths; therefore, bandpass filters are used to limit the IR spectrum to specific wavelengths used in the particular transmitter design.

Transmitters are calibrated using gas mixtures with known CO_2 concentration. Often the calibration gas is a N_2/CO_2 mixture. The gas mixture is dry in that it does not contain water vapor. Calibration gases are available in various CO_2 concentrations with various grades of accuracy. The accuracy of the CO_2 gas concentration in the mixture is expressed either as deviation in CO_2 ppm (i.e., ± 10 ppm) or as a percentage of the CO_2 concentration (i.e., 1%). For a simple two-point calibration, the "zero" gas is N_2 and the "span" gas is 2000 ppm CO_2 (with N_2 as the base gas). Multi-point calibrations utilize additional CO_2/N_2 mixtures. As discussed above, temperature and pressure affect the sensor output; therefore, the temperature and pressure at which calibration is performed must be specified.

Measuring Carbon Dioxide

Different approaches to measuring CO_2 concentration are based on quantifying different physical properties of the mixture of CO_2 in air. Carbon dioxide concentration in air can be expressed in a variety of forms with the most common forms being parts per million by volume (ppm), mass of CO_2 per unit volume of mixture (e.g. mg/m^3), percent by volume, and partial pressure. One ppm is 1 part of CO_2 in 1,000,000 parts of air. The 2005 ASHRAE Handbook–*Fundamentals* suggests conversion between ppm and mg/m^3 as:

$$ppm = \frac{0.6699 * (459.7 + t)}{M * p} \; (mg/m^3) \qquad \text{(Eq. 1)}$$

where

M = molecular weight of CO_2 = 44.0098 kg/kmol
p = mixture pressure, psia
t = mixture temperature, °F

This equation is based on ideal gas behavior, but is generally acceptable for dilute CO_2 dispersed in ambient air. At 77 °F (25 °C) and 14.7 psia (101.35 kPa), 1 ppm is equivalent to 1.8 mg CO_2 per m^3 of air.

Indoor Environment CO_2 Concentrations

Typical Outdoor Air	325 – 400 ppm
Typical Office Environment	600 – 800 ppm
DVC Control Range	600–1100 ppm (outdoor air + 700 ppm)
Occupational Safety and Health Administration (OSHA)	5,000 ppm average over 8 hours
National Institute for Occupational Safety and Health (NIOSH)	30,000 ppm maximum over 15 minutes
American Conference of Governmental Industrial Hygienists (ACGIH)	
Adult Exhaled Breath	35,000 – 50,000 ppm

Operational and environmental conditions affect the performance of all CO_2 sensors. An unavoidable operational effect is a result of the degradation of the IR light source over time. Since the principle of operation is based on measured attenuation of the IR beam, a decrease in lamp intensity affects the sensor output. Environmental conditions such as dust, aerosols and chemical vapors may also affect the transmitter performance by altering the optical properties of the sensor components due to long-term exposure to these contaminants. To minimize the effects of air-born particulates, sensor manufacturers use a filter media across the opening of the sensor's optical cavity where the air sample is analyzed. Various techniques are used by CO_2 transmitter manufacturers to compensate for the long-term affects of operational and environmental conditions. These techniques have led to the three basic configurations currently used in NDIR transmitters. These configurations are disused in the next section.

Sensor Configurations

Three configurations used for HVAC grade CO_2 transmitters are (1) single-beam single-wavelength, (2) dual-beam single wavelength and (3) single-beam dual wavelength. The term "beam" used by transmitter manufacturers leads to confusion on the technology employed in the sensor configuration. A single lamp can produce multiple "beams", so when the term "dual beam" is used, it is not clear if one or two lamps are employed. Therefore, in this report the sensor configurations are referred to as (1) single-lamp single-wavelength, (2) dual-lamp single wavelength and (3) single-lamp dual wavelength. These configurations are schematically illustrated in Figure 1.

Single-lamp single-wavelength – Transmitters that use this configuration (Figure 1a) incorporate an "automatic baseline adjustment" algorithm in the transmitter's electronics package. The algorithm "adjusts" the transmitter's output according to the minimum CO_2 concentration observed over a time period. It is assumed that the minimum CO_2 concentration corresponds to the outdoor CO_2 concentration. A value of 400 ppm is commonly used as the value for the outdoor CO_2 concentration level to which the transmitter output is set when the automatic adjustment is made. The programming logic used in the algorithm varies among transmitter manufacturers. Some algorithms adjust the baseline level as frequently as every hour and reset the baseline directly to 400 ppm. Other algorithms perform adjustments based on several weeks of sampling and only make incremental step adjustments to the baseline value. It is important to note that transmitters which use any algorithm to adjust the transmitter output must only be used in applications where they will be periodically exposed to ambient CO_2 concentrations.

Principals of Infrared Analysis

Infrared light interacts with most molecules by exciting molecular vibrations and rotations. When the IR frequency matches the natural frequency of the molecule, some of the IR energy is absorbed. While carbon dioxide has several absorption bands, the 4.26 µm band is the strongest. At this wavelength absorption by other common components of air are negligible. Hence, CO_2 transmitters use the 4.26 µm band. Quantitative analysis of a gas sample is based on the Beer-Lambert law (Equation 2), which relates the amount of light absorbed to the sample's concentration and path length.

$$A = \alpha bC = [\log_{10} (I_0 / I)] \qquad \text{(Eq. 2)}$$

Where:

A = absorbance

I = IR light intensity reaching detector with absorbing media in beam path.

I_0 = IR light intensity reaching detector with no absorbing media in beam path.

α = molar absorption coefficient (absorption coefficient of pure components of interest at analytical wavelength); the units depend on those chosen for b and c.

b = beam path length.

C = molar concentration of sample component.

From Equation 2 it is evident that the attenuation of an IR beam at 4.26 µm is proportional to the number density of CO_2 molecules in the optical path. For gases, the molecular density is directly proportional to the pressure and inversely proportional to the temperature. Thus temperature and pressure corrections must be applied when using IR absorption to determine CO_2 concentrations.

Dual-lamp single wavelength – The dual-lamp single wavelength configuration (Figure 1b) uses two IR sources (lamps). One lamp pulses at approximately 3 Hz (typical pulse rate for all IR lamps) while the second lamp pulses much less frequently (on the order of one pulse every 24 hours). Due to the relatively infrequent pulsing of the second lamp, the ageing of the second lamp is much less than the ageing of the first lamp, and is used as a reference for transmitter compensation.

Single-lamp dual wavelength – Figures 1c and 1d illustrate two configurations which are both referred to as single-lamp dual wavelength. The principle behind either configuration is understood by examining the spectral properties of the filters used. As illustrated in Figure 2, Filter 1 passes IR radiation in a portion of the IR spectrum that contains no absorption bands for any of the gaseous commonly found in air. For this wavelength, the output from the IR detector is independent of the mixture of gases in the air sample; therefore, this output provides a reference signal used for sensor compensation. Filter 2 passes 4.26 μm IR radiation which is used for the CO_2 concentration measurement.

The configuration shown in Figure 1d uses a silicone based electronically tunable Fabry-Perot Interferometer (FPI) in front of the detector. This solid-state device provides an electronic method of switching between the band pass filters, thus allowing for sensor compensation using a single filter-detector package.

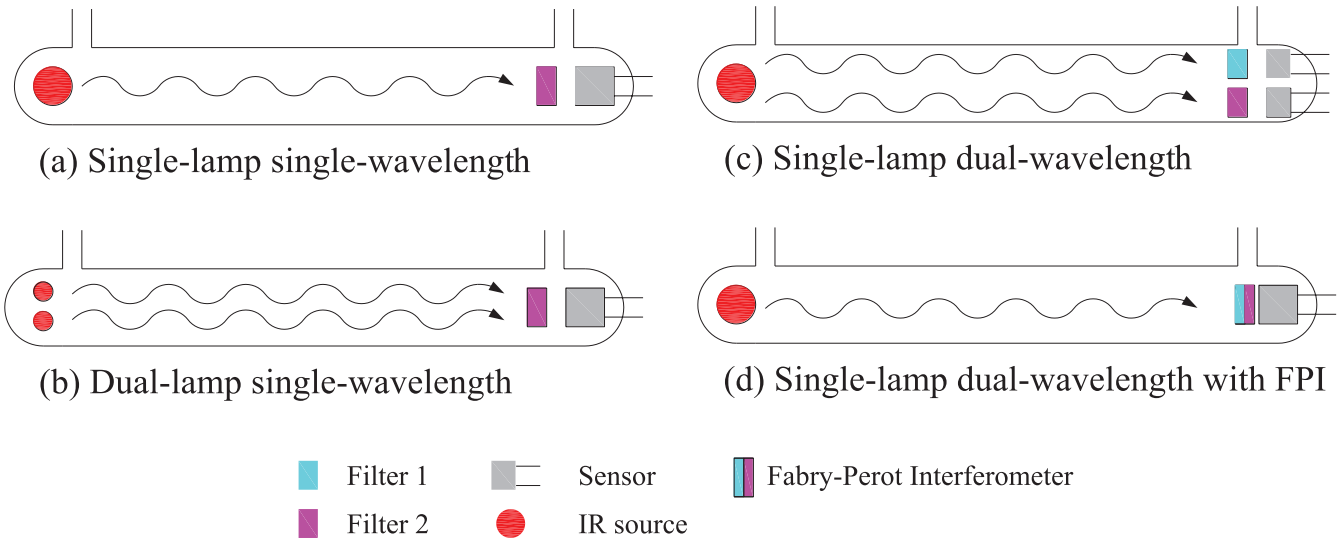


Figure 1. NDIR sensor configurations.

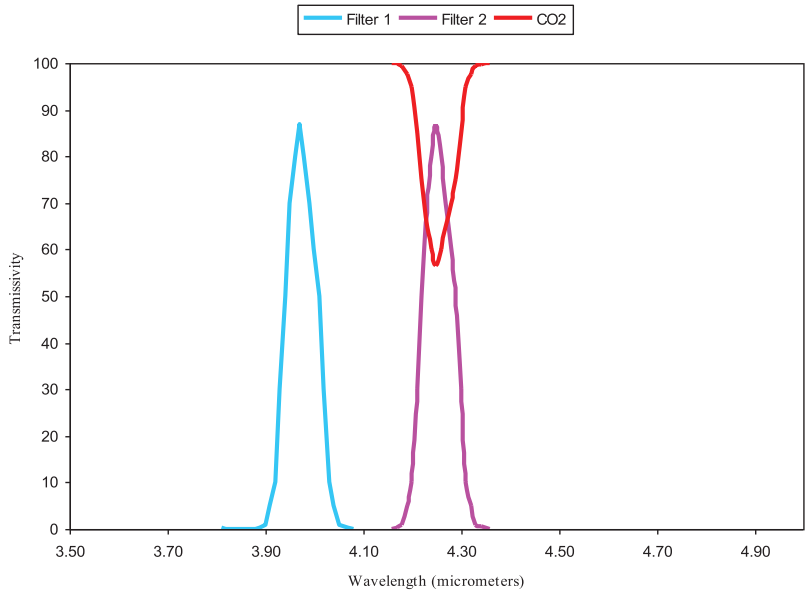


Figure 2. Spectral transmissivity data for CO_2 and filters.

Choosing the Right CO_2 Transmitter

Specifying or selecting a CO_2 transmitter is dictated by the requirements of its intended application. Transmitter selection requires careful consideration of several factors and how important they are to the application. As stated by manufacturers of transmitters that employ an "automatic baseline adjustment", these transmitters should not be used in applications where the transmitters are continuously exposed to CO_2 concentrations above normal outdoor CO_2 concentrations. The main factors that should be considered are discussed below.

Accuracy

Accuracy is the capability of an instrument to indicate the true value of the measured quantity. It is an important parameter in the selection of CO_2 transmitters.

Most manufacturers' data sheets provide only a partial view of transmitter performance. Transmitters that are calibrated at laboratory controlled temperature, pressure, CO_2 concentration, and humidity conditions may not reflect actual field conditions to which the transmitter will be subjected. It is therefore important to know the calibration standard that was used, the temperature, pressure, CO_2 concentration(s), and humidity condition at which the transmitter was calibrated, how transmitter performance is affected by varying temperature and humidity, and how ageing of the transmitter will affect its performance.

Most manufacturers calibrate and report transmitter accuracy at or around 77°F (25°C), and 14.7 psia. All CO_2 transmitters are temperature, pressure, and humidity sensitive, and transmitter performance can be affected when subjected to an environment significantly different from the environment used for calibration. Compensation for temperature, pressure, and humidity conditions may be desirable for better accuracy of a transmitter. Most manufacturers specify operating ranges of temperature and humidity for their CO_2 transmitters as 32°F to 122°F (0°C to 50°C) and 0 to 90% RH (non-condensing) respectively.

The term accuracy also covers a few other measures of performances such as hysteresis, linearity and repeatability. Hysteresis is the summation of all effects, under constant environmental conditions, that cause the output of an instrument to assume different values at a given stimulus point when that point is approached with increasing stimulus and with decreasing stimulus. Linearity is the straight-line behavior of the transfer curve between an input and an output; that condition prevailing when the output is directly proportional to input. Repeatability is the variation in measurements on the same quantity and under the same conditions. According to the Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results, repeatability conditions include the same measurement procedure, the same observer, the same measuring instrument used under the same conditions, the same location, and repetition over a short period of time.

Operating Range

Range is the upper and lower limits between which an instrument's input can be received and for which the instrument is calibrated. The transmitter must be capable of providing an adequate change in its output signal over the expected input range. An operating range of 0 to 2000 ppm should be optimum for building HVAC application. Some transmitters' have a range that is adjustable within certain limits.

Response Time

Building HVAC applications have response times on the order of minutes. Most manufacturing companies specify response times for their CO_2 transmitters as being less than 1 minute for up to a 90% step change while a few manufacturers specify it as 2 to 3 minutes.

Maintenance and Calibration

Maintenance requirements depend on the type of technology used in the transmitter, environmental conditions and exposure to contaminants. Most of the HVAC grade NDIR CO_2 transmitters' recommended calibration time varies from one to five years.

Calibration methods vary, as do their cost and the resulting accuracy of calibration. Normally CO_2 transmitters are calibrated for zero and span using a gas of known CO_2 concentration.

Long-term Stability

Long-term stability refers to how transmitter accuracy drifts over time and determines the frequency of calibration. A stable transmitter would require fewer calibrations. Units used to evaluate long-term stability are percent full scale per year and ppm per year.

CO_2 Transmitter Cost

First costs will vary depending on transmitter accuracy and the type of application. In addition to initial cost, the long-term costs, including transmitter recalibration, replacement and maintenance, must be considered.

NBCIP Testing

Manufacturer Information

NBCIP reviewed technical publications, trade magazine and internet website information to identify current manufacturers of wall-mounted CO_2 transmitters suitable for HVAC application. Utilizing the product literature from each manufacturer, specifications for the various transmitters were reviewed. The majority of the transmitters available use a form of the NDIR method for gas detection.

Most manufacturers provide both wall and duct-mounted transmitters. Transmitters are available with or without a display, which shows the CO_2 level in ppm. Some transmitters have a built-in relay, which will activate when the CO_2 concentration reaches a prescribed level.

The range for most available transmitters is 0 to 2,000 ppm. Some provide field adjustable settings up to 10,000 ppm. Accuracy varies among the various transmitters. The time between calibrations varies from 1 to 5 years for most transmitters with the exception of those, which incorporate an "Automatic Baseline Adjustment" algorithm. This approach adjusts the transmitter signal based on CO_2 levels measured during non-occupied periods.

For the purpose of this study, it was determined that CO_2 transmitters designated for HVAC service would be tested. Because wall mounted units are more commonly used in HVAC applications, ducted-mounted transmitters were not considered. Given the CO_2 concentration levels found acceptable for indoor air quality, only transmitters having a range from 0 to 2,000 ppm were considered. Based on these criteria, fifteen CO_2 transmitter models from thirteen manufacturers were identified. Figure 3 illustrates the transmitters selected.

Technical information for the fifteen selected CO_2 transmitters is compiled in Table 1. The technical information is based on the manufacturer's product specifications and technical data published at the time the CO_2 transmitters were purchased (from January 2007 to August 2007). The manufacturer's product specifications were obtained from technical data downloaded from the manufacturer's website, product information from the manufacturer's web page or technical documentation shipped with the product. It should be noted manufacturers reserve the right that product specifications are subject to change without notice.

NBCIP purchased three CO_2 transmitters of the same model to use in the performance testing. The models were organized into three groups (A, B and C). Transmitters were purchased over a period of several months to increase the possibility that they originated from different manufacturing lots. At the time of purchasing the second lot of transmitters, an e-mail (see Appendix A) was sent to each manufacturer stating the intended use of the transmitters being purchased. The e-mail requested specific instructions for ordering the transmitter as well as a technical contact person. If no specific ordering instruction were received from the manufacturer, then transmitters were ordered via the company web site. As each transmitter model arrived, it was assigned to a group (A, B or C). Thus, each group ultimately contained fifteen transmitters, one from each model.

Prior to performance testing, NBCIP subjected each group of transmitters to the manufacturer stated voltage input to ensure they were in working order. All transmitters received were found to be in working order.

Figure 3. Wall-mounted CO_2 transmitters used in NBCIP testing.

Table 1. Technical information for carbon dioxide transmitters tested by NBCIP.

Manufacturer	AirTest Technologies	AirTest Technologies	Automation Components Inc.	Digital Control Systems, Inc.	Greystone Energy Systems, Inc.	Honeywell Inc.	Intec Controls
Model Number	TR9290	EE80-2CT3	ACI/CO2-VDC-R	AirSense™ M307	CDDIA 2000	C7232A1016	I-310e
Price paid by NBCIP	$186	$273	$248	$195	$402	$277	$231
Technology (NDIR)	Single lamp, single wavelength, automatic baseline adjustment	Two lamps, single wavelength	Single lamp, single wavelength, automatic baseline adjustment	Single lamp, single wavelength, automatic baseline adjustment	Single lamp, single wavelength, automatic baseline adjustment	Single lamp, single wavelength, automatic baseline adjustment	Single lamp, single wavelength, automatic baseline adjustment
Accuracy	± 1% of measurement range + 5% of measured value	< ± (50 ppm + 2% of measure value) at 20°C	± 50 ppm or + 3% of reading (@ 25°C at standard pressure)	± 5% of reading or 75 ppm, (whichever is greater)	± 75 ppm or 3% of reading (whichever is greater) (15°C to 32°C (59°F to 90°F))	± (30 ppm + 2% of reading)	± 5% of reading or ± 75 ppm
Operating Range	32°F to 122°F (0°C to 50°C) 0% to 95% RH	23°F to 131°F (–5°C to 55°C) 0% to 90% RH	59°F to 90°F (15°C to 32°C) 0% to 95% RH	32°F to 122°F (0°C to 50°C) 5% to 95% RH	32°F to 122°F (0°C to 50°C) 0% to 95% RH	32°F to 122°F (0°C to 50°C) 0% to 95% RH	32°F to 122°F (0°C to 50°C) 0% to 90% RH
Temperature Sensitivity	5 ppm/°C	5 ppm/°C	+/– 0.15% FS/°C	NA	0.2 %FS/°C	NA	NA
Pressure Sensitivity	NA	NA	0.13% of reading per mmHg from 760 mmHg	NA	0.13% of reading per mm Hg	1.4% change in reading per 1 kPa deviation from 100 kPa.	Calibrated for sea level, adjustable to altering altitude levels by setting correction multiplier
Calibration Interval	Automatic baseline correction for self calibration (15 years) lifetime self calibration (15 years)	15 Years	ABC Logic™ Automatic self calibration software	5 year	5 year	Typically, calibration is unnecessary	Three to five years, Span only, zero adjustment, automatically self-tuned
Response Time	T90 = < 2 minutes	T63 = < 90 seconds	< 2 minutes	NA	2 minutes for 90% step change	2 minutes	Less than 1 minute

Table 1. (Continued)

Manufacturer	Johnson Controls Inc.	Sensata (Texas Instruments)	Siemens	Telaire	Telaire	Vaisala	Veris Industries	Vulcain
Model Number	CD-WA0-00-0	4GS-1	QPA2000	Ventostat 8001	Ventostat 8102	GMW21	CWE SC	90DM4SM-C-2000
Price paid by NBCIP	$433	$444	$252	$265	$379	$787	$426	$369
Technology (NDIR)	Single lamp, dual wavelength	Two lamps, single wavelength	Two lamps, single wavelength	Single lamp, single wavelength, automatic baseline adjustment	Single lamp, dual wavelength	Single lamp, dual wavelength	Single lamp, single wavelength, automatic baseline adjustment	Two lamps, single wavelength
Accuracy	< ± [30 ppm + 2.0% of reading] at 68°F (20°C)	± 75 ppm if 0–1500 ppm: ± 5% if > 1500ppm (readings @ standard pressure 760 mm Hg & 25°C)	≤ ± 50 ppm + 2% of measured value	±100 ppm or 7% whichever is greater	± 50 ppm or 5% whichever is greater (7% for levels over 1500 ppm) @ 60°F–90°F (15°C–32°C)	< ± [30ppm + 2% of reading] at 25°C (77°F)	± 30 ppm ± 5% of measured value	± 100 ppm + 3% of reading
Operating Range	23°F to 113°F (–5°C to 45°C) 0% to 85% RH	32°F to 122°F (0°C to 50°C) 5% to 95% RH	23°F to 113°F (–5°C to 45°C) 0% to 85% RH	60°F to 90°F (15°C to 32°C) 0% to 95% RH	32°F to 122°F (0°C to 50°C) 0% to 95% RH	23°F to 113°F (–5°C to 45°C) 0% to 85% RH	32°F to 122°F (0°C to 50°C) 0% to 95% RH	32°F to 100°F (0°C to 40°C) 0% to 95% RH
Temperature Sensitivity	< 0.056% of Full Scale/°F (< 0.1% of Full Scale/°C)	5 ppm/°C over operating temperature	+/– 2 ppm/°C	NA	NA	0.15 %FS /°C (reference 25°C)	NA	NA
Pressure Sensitivity	Without compensation for an altitude range of 0 to 1,969 ft (0 to 600m) above sea level. To compensate for higher altitudes, see the installation instructions.	0.19% of reading per mm Hg	NA	Add 0.13% of reading per mm Hg decrease from 760 mm Hg	Add 0.13% of reading per mm Hg decrease from 760 mm Hg	NA	NA	NA
Calibration Interval	NA	3 years	Not required	ABC Logic™ Automatic self calibration software	5 year calibration guarantee	5 year	5 year	NA
Response Time	1 Minute	< 30 seconds to 63% of step changes	(0 to 63%) 1 minute	0-90% < 1 minute	0-90% < 1 minute	(0 to 63%) 1 minute	< 60 seconds for 90% step change	Less than 60 sec. (for 90% of the reading)

Notes:

1. The information in this table was obtained first from the product data supplied with the transmitters, or next from the product documents available on the mfg web site, or last from the mfg web page.
2. NA indicates that the information was not available in the manufacturer's product literature.
3. NBCIP tested the wall-mounted carbon dioxide transmitters using a supply voltage of 24 VDC or 24VAC as specified by manufacturers.
4. NBCIP tested the wall-mounted carbon dioxide transmitters using VDC output. Current output from Honeywell transmitters was converted to VDC using 1% 250-ohm resistors.
5. None of the manufacturers reported humidity sensitivity of their transmitters.

Testing Methods

Performance testing of the CO_2 transmitters was performed under the supervision of NBCIP in a research laboratory located in the H.M. Black Engineering Building at Iowa State University. Performance testing was conducted in an experimental test apparatus specifically designed and built for this project. Refer to the sidebar for detailed information on the Test Apparatus. The test conditions and procedures by which the transmitters were tested followed a method of test developed by NBCIP.

Test Apparatus

Figure 4 is a schematic diagram of the test system used for the performance testing of the transmitters. The test system allowed for independent control of pressure, temperature, relative humidity and CO_2 concentration within the test chamber. The test chamber was designed to hold an entire group of transmitters to assure that each transmitter in the group experienced the same test conditions.

Figure 5 illustrates the arrangement of the transmitters inside the test chamber. In addition to the transmitters under test, the figure shows a Vaisala GMP343 transmitter and a small circulating fan. The GMP343 is a research-grade CO_2 transmitter and was only used as a "reference" measurement. This transmitter is referred to as "test chamber CO_2 transmitter". The circulating fan provided assurance that conditions within the test chamber were "well mixed". A fixture was designed to hold the transmitters under test, the reference transmitter and the fan. This fixture allowed for the entire group of transmitters to be moved as a single assembly. Figure 6 (next page) is a photograph of a group of transmitters mounted on a fixture.

An Environics® S-4000 gas mixing system was used to provide a known mixture of CO_2 and N_2 to the test chamber. This gas mixture can be "bubbled" through a deionized water column to add water vapor (humidity). The system is capable of producing gas mixtures from 334 to 3333 ppm CO_2 (1% accuracy) at a flow rate of 3 liters/min with relative humidity ranging from dry gas (no humidification) to approximately 80% relative humidity (at 14.7 psia and 73 °F).

The pressure, temperature and relative humidity inside the test chamber are measured using an Omega PX209 absolute pressure transmitter and a Vaisala HMT334 humidity/temperature transmitter. The technical specifications for these instruments are provided in Appendix B.

A Hewlett Packard 3457A multimeter and a Hewlett Packard 3488A switch/control unit was used to measure output from the CO_2 transmitters, temperature transmitter, humidity transmitter, and pressure transmitter.

(*Continued on page 10*)

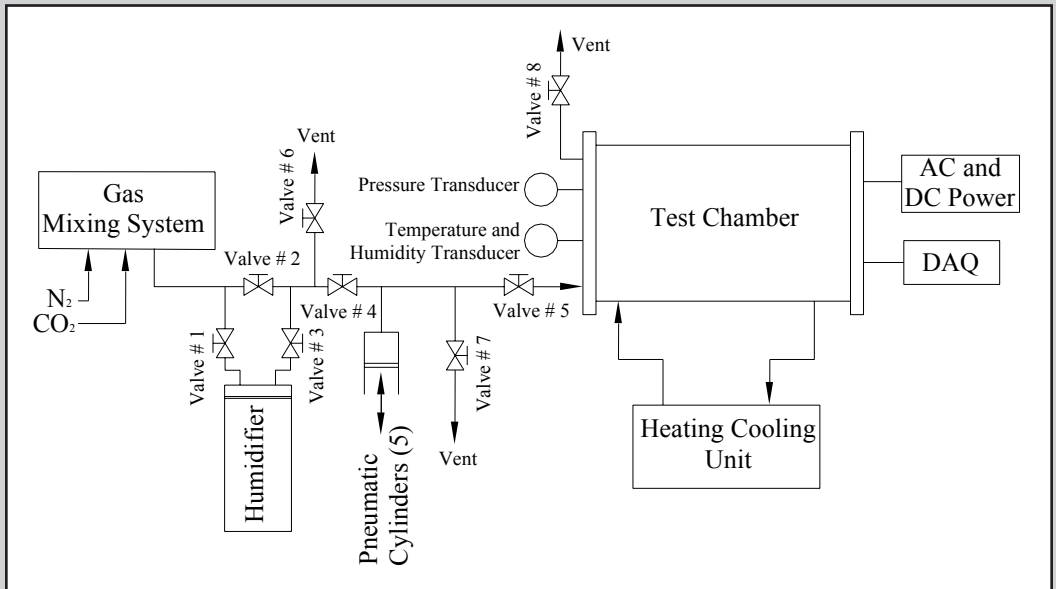


Figure 4. Schematic of the test system.

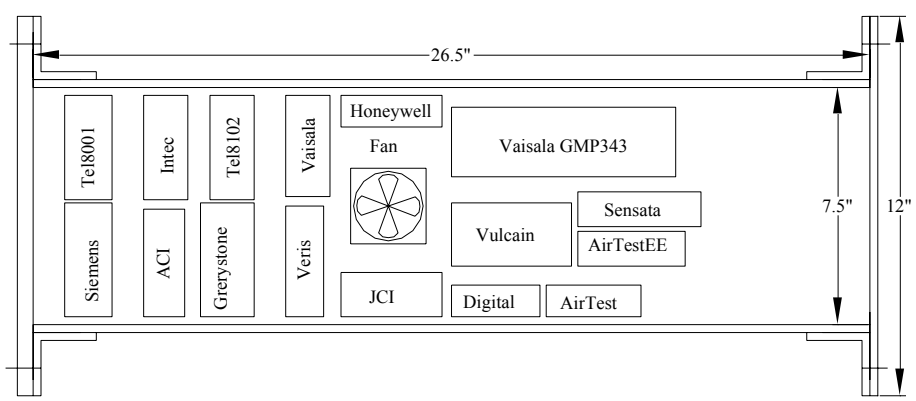


Figure 5. Arrangement of transmitters inside the test chamber.

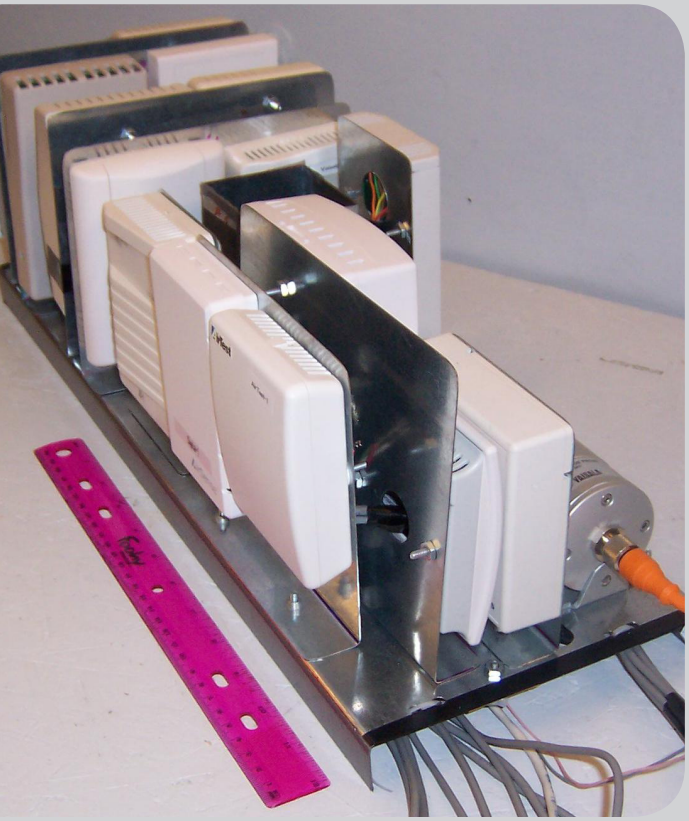


Figure 6. Test transmitters mounted on fixture.

(Continued from page 9)

National Instruments LabView software was used in conjunction with the multimeter and switch/control unit as a data acquisition system to record all transmitter data.

Adding water vapor to a dry gas mixture changes the mole fraction of the gases in the mixture; therefore, the concentration of CO_2 in a mixture will decrease as water vapor content increases. To achieve a desired CO_2 concentration under humid conditions, one must account for this effect and adjust the CO_2 concentration in the dry-gas mixture accordingly. The ideal gas model was used to calculate this adjustment. The procedure is discussed in Appendix C.

Accuracy, Linearity, Repeatability, and Hysteresis

Accuracy, linearity, repeatability, and hysteresis of the transmitters were evaluated by varying the CO_2 concentration while maintaining the chamber relative humidity, temperature and pressure at 40%, 73°F (22.8°C) and 14.7 psia (101.35 kPa), respectively.

The tests were performed in the following sequence:

- Initially the CO_2 concentration in the test chamber was set at 400 ppm. The gas mixing system was run continuously providing continuous purge. Data collection at this condition and at all other conditions followed a protocol described below.
- Holding the chamber humidity, temperature, and pressure steady, the CO_2 concentration was increased to 1800 ppm in 350 ppm increments. These measurements, including the initial measurement at 400 ppm, are referred to as the forward measurements. (Refer to data points 1 through 5 in Figure 7)
- After reaching 1800 ppm, the test was reversed, i.e, CO_2 concentration being decreased from 1800 ppm to 400 ppm in 350 ppm increments while maintaining the chamber humidity, temperature, and pressure steady. These measurements are referred to as the reverse measurements. (Refer to data points 6 through 9, Figure 7)
- Once the 400 ppm level was attained, the CO_2 concentration was increased to 1450 ppm in 350 ppm increments maintaining the chamber humidity, temperature, and pressure steady. These measurements (data points 10 through 12, Figure 7) are also forward measurements.

The output from all transmitters was recorded while the environmental condition within the test chamber settled to the steady-state conditions defined in Table 2. For clarity, these data are referred to as "settling data" and data collected at steady-state conditions for quantifying the performance of the test transmitters are referred to as "test data." Interpreting Table 2, to attain and maintain a steady-state condition in the test chamber, the following conditions were maintained for 10 minutes prior to the collection of the test data as well as throughout the collection of the test data: CO_2 concentration reading from the test chamber CO_2 transmitter did not vary more than ± 20 ppm from its mean output, test chamber humidity transmitter output did not vary more than ± 2.5% from the desired relative humidity, test chamber temperature transmitter output did not vary more than ± 1.8°F (1°C) from the desired temperature, and test chamber pressure transmitter output did not vary more than ± 0.14 psia (0.965 kPa) from the desired pressure.

Data were recorded from all test transmitters once steady-state conditions were established. At each test condition, 10 samples of transmitter output collected at one-minute intervals were averaged and used to report the "Measured CO_2 Concentration" accuracy test data for the transmitter.

Accuracy and linearity were evaluated using the first forward and reverse measurements (points 1 through 9, Figure 7). Repeatability was evaluated using the two forward measurements at 750, 1100 and 1450 ppm (data points 2 and 10, 3 and 11, and 4 and 12, Figure 7). Hysteresis was evaluated using the first forward measurement and the reverse measurement at 750, 1100 and 1450 ppm (data points 2 and 8, 3 and 7, and 4 and 6, Figure 7).

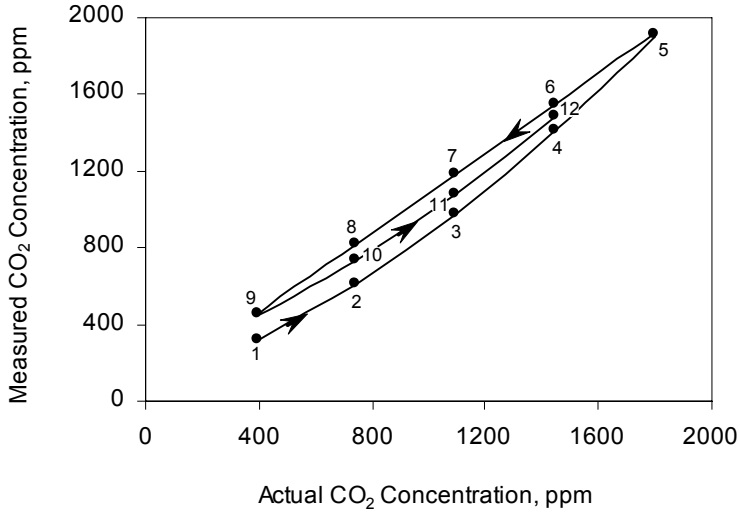


Figure 7. Example data set to illustrate numbering scheme used to identify data points.

Table 2. Steady-state conditions for the accuracy, linearity, repeatability and hysteresis tests.

Parameter	Steady-state condition
CO_2 concentration	Within ± 20 ppm of mean output from the test chamber CO_2 transmitter for 10 minutes prior to and during the collection of the test data
Temperature	Within ± 1.8°F (1°C) of the desired temperature condition measured by the test chamber temperature transmitter for 10 minutes prior to and during the collection of the test data
Pressure	Within ± 0.14 psia (0.965 kPa) of the desired pressure condition measured by the test chamber pressure transmitter for 10 minutes prior to and during the collection of the test data
Relative humidity	Within ± 2.5% of the desired relative humidity measured by the test chamber humidity transmitter for 10 minutes prior to and during the collection of the test data

Humidity Effects

The effect of humidity on CO_2 transmitters was evaluated by varying the relative humidity in the test chamber while maintaining the chamber CO_2 concentration, temperature, and pressure at 1100 ppm, 73°F (22.8°C) and 14.7 psia (101.35 kPa), respectively.

The tests were performed in the following sequence:

- A continuous feed of a humidified gas mixture was used to produce 20% relative humidity in the test chamber. Data collection at this condition and at all other conditions followed the same test procedure described above with steady-state conditions again being defined by Table 2.
- Holding the CO_2 concentration, temperature, and pressure steady, the test chamber relative humidity was increased first to 40% and then to 60%.

At each test condition, 10 samples of transmitter output collected at one-minute intervals were averaged and used to report the "Measured CO_2 Concentration" humidity sensitivity test data for the transmitter.

Temperature Effects

The effect of temperature on CO_2 transmitters was evaluated by varying the temperature in the test chamber while maintaining the chamber CO_2 concentration and pressure at 1100 ppm, and 14.7 psia (101.35 kPa), respectively. Relative humidity in the test chamber was maintained at 40% at 73°F (22.8°C) temperature. The test chamber temperature was varied while maintaining the composition of the gas mixture steady. Hence, the absolute humidity remained the same; although, the relative humidity changed with temperature.

The tests were performed in the following sequence:

- Initially the temperature in the test chamber was set at 73°F (22.8°C). The gas mixing system ran continuously allowing continuous purge. Data collection at this condition and at all other conditions followed the protocol described below.
- Holding the CO_2 concentration, gas mixture composition, and pressure steady, the test chamber temperature was decreased first to 66°F (18.9°C) and then increased to 80°F (26.7°C).

Output from transmitters was recorded while the test environment settled to the steady-state conditions defined in Table 3. For clarity, these data are referred to as "settling data" and data collected at steady-state conditions for quantifying the performance of the test transmitters are referred to as "test data". Interpreting Table 3, to attain and maintain a steady-state condition in the test chamber, the following conditions were maintained for 10 minutes prior to the collection of the test data as well as throughout the collection of the test data: CO_2 concentration reading from the test chamber CO_2 transmitter did not vary more than ± 20 ppm from its mean output, test chamber temperature transmitter output did not vary more than ± 1.8°F (1°C) from the desired temperature, test chamber pressure transmitter output did not vary more than ± 0.14 psia (0.965 kPa) from the desired pressure, and test chamber relative humidity transmitter output did not vary more than 2.5% from the desired relative humidity at 73°F temperature.

Data were recorded from all test transmitters once steady-state conditions were established. At each test condition, 10 samples of transmitter output collected at one-minute intervals were averaged and used to report the "Measured CO_2 Concentration" temperature sensitivity test data for the transmitter.

Table 3. Steady-state conditions for the temperature sensitivity test.

Parameter	Steady-state condition
CO_2 concentration	Within ± 20 ppm of mean output from the test chamber CO_2 transmitter for 10 minutes prior to and during the collection of the test data
Temperature	Within ± 1.8°F (1°C) of the desired temperature condition measured by the test chamber temperature transmitter for 10 minutes prior to and during the collection of the test data
Pressure	Within ± 0.14 psia (0.965 kPa) of the desired pressure condition measured by the test chamber pressure transmitter for 10 minutes prior to and during the collection of the test data
Relative humidity	Within ±2.5% of the desired relative humidity at 73°F temperature, measured by the test chamber humidity transmitter for 10 minutes prior to and during the collection of the test data

Pressure Effects

The effect of pressure on CO_2 transmitters was evaluated by varying the pressure in the test chamber while maintaining the chamber CO_2 concentration and temperature at 1100 ppm and 73°F (22.8°C), respectively. Relative humidity in the test chamber was maintained at 40% at 14.7 psia (101.35 kPa) pressure. The test chamber pressure was varied while maintaining the composition of the gas mixture steady. Hence, the absolute humidity remained fixed; however, the relative humidity varied at pressures other than 14.7 psia (101.35 kPa). The test was conducted at three pressures: 14.70 psia (101.35 kPa), 13.25 psia (91.35 kPa), and 11.80 psia (81.35 kPa). The pressure levels correspond to standard atmospheric pressures for altitudes corresponding to sea level, 2838 feet (865 meters) and 5948 feet (1813 meters) above sea level.

The gas mixture at the desired CO_2 concentration and relative humidity [at 73°F (22.8°C) temperature and 14.7 psia (101.35 kPa) pressure], flowed continuously through the test chamber until the CO_2 concentration, relative humidity, temperature, and pressure of the gas in the chamber had stabilized.

The tests were performed in the following sequence:

- Initially the pressure in the test chamber was set at 14.7 psia (101.35 kPa). At a steady state condition, the test chamber was isolated. Data collection at this condition and at all other conditions followed the protocol described below.
- Holding the CO_2 concentration, gas mixture composition, and temperature steady, the test chamber pressure was changed first to 13.25 psia (91.35 kPa), and then to 11.8 psia (81.35 kPa).

Output from transmitters was recorded while the test environment settled to the steady-state conditions defined in Table 4. For clarity, these data are referred to as "settling data" and data collected at steady-state conditions for quantifying the performance of the test transmitters are referred to as "test data". Interpreting Table 4, to attain and maintain a steady-state condition in the test chamber, the following conditions were maintained for 10 minutes prior to the collection of the test data as well as throughout the collection of the test data: CO_2 concentration reading from the test chamber CO_2 transmitter did not vary more than ± 20 ppm from its mean output, test chamber temperature transmitter output did not vary more than ± 1.8°F (1°C) from the desired temperature, test chamber pressure transmitter output did not vary more than ± 0.14 psia (0.965 kPa) from the desired pressure, and test chamber relative humidity transmitter output did not vary more than 2.5% from the desired relative humidity at 14.7 psia (101.35 kPa) pressure.

Data were recorded from all test transmitters once steady-state conditions were established. Requirements for steady-state conditions are detailed in the section below. At each test condition, 10 samples of transmitter output collected at 1 minute intervals were averaged and used to report the "Measured CO_2 Concentration" pressure sensitivity test data for the transmitter.

Table 4. Steady-state conditions for the pressure sensitivity test.

Parameter	Steady-state condition
CO_2 concentration	Within ± 20 ppm of mean output from the test chamber CO_2 transmitter for 10 minutes prior to and during the collection of the test data
Temperature	Within ± 1.8°F (1°C) of the desired temperature condition measured by the test chamber temperature transmitter for 10 minutes prior to and during the collection of the test data
Pressure	Within ± 0.14 psia (0.965 kPa) of the desired pressure condition measured by the test chamber pressure transmitter for 10 minutes prior to and during the collection of the test data
Relative humidity	Within ±2.5% of the desired relative humidity at 14.7 psia pressure, measured by the test chamber humidity transmitter for 10 minutes prior to and during the collection of the test data

NBCIP Test Results

Accuracy

Before discussing the results for each transmitter, it is important to note that for some transmitters the maximum output voltage (nominally 10 VDC) was reached when the transmitters were exposed to the higher level (1800 ppm) CO_2 concentration test conditions. This is illustrated in Figure 8 which shows the output voltage from one of the transmitters as the CO_2 concentration in the test chamber increases. As seen in the figure, when the CO_2 concentration reaches approximately 1700 ppm, the output voltage of the transmitter is 10 VDC. Since this is the maximum voltage produced by the transmitter, further increases in CO_2 concentration do not produce any change in the output voltage. For this transmitter, the output reading would indicate 2000 ppm for any CO_2 concentration in excess of 1700 ppm. The transmitter is said to be saturated. For all transmitter models tested, the operating range of each transmitter is 0 to 2000 ppm. Saturated data points were not considered for analysis.

Figure 9 shows the results of NBCIP's evaluations of CO_2 transmitter accuracy for all three transmitters of each model tested. NBCIP calculated the deviation of the measured CO_2 concentration from the actual CO_2 concentration. The measured CO_2 concentration is calculated by using the average of the first forward and reverse measurements at the same test conditions. Manufacturer stated accuracy for each CO_2 transmitter model is provided in Table 1. The stated accuracy is graphically portrayed on each figure as a gray box. For most models, the accuracy is a function of the reading; therefore, as the CO_2 concentration increases, the accuracy values become larger.

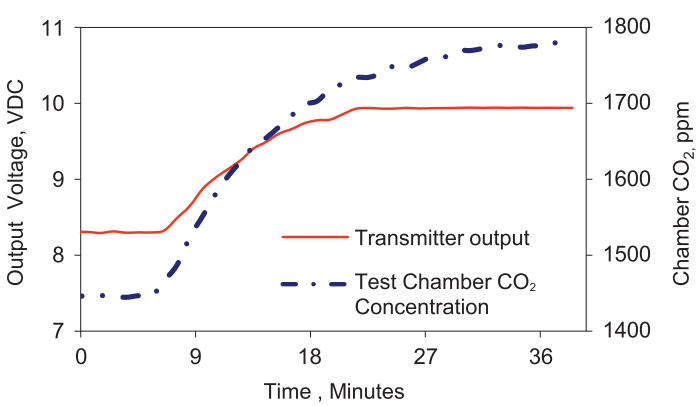
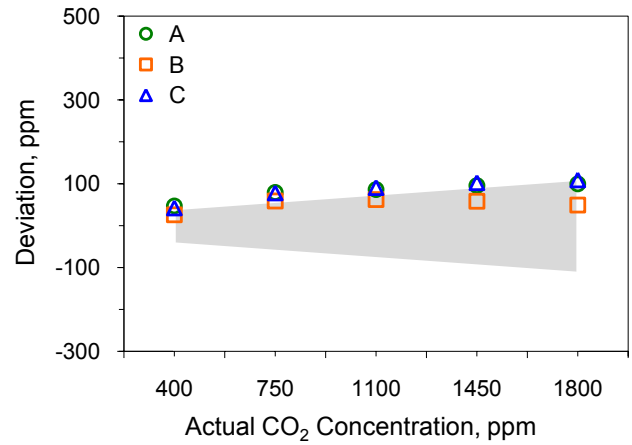
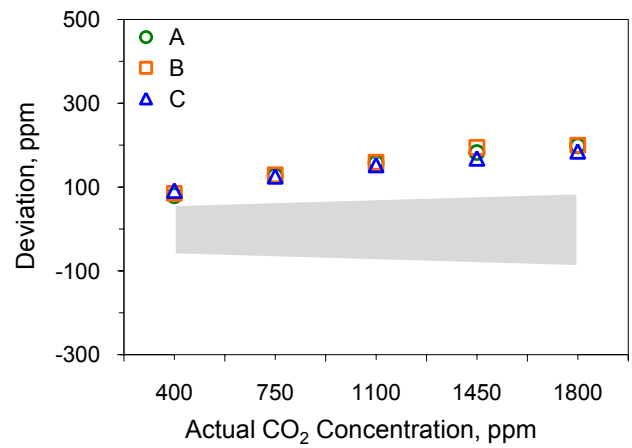


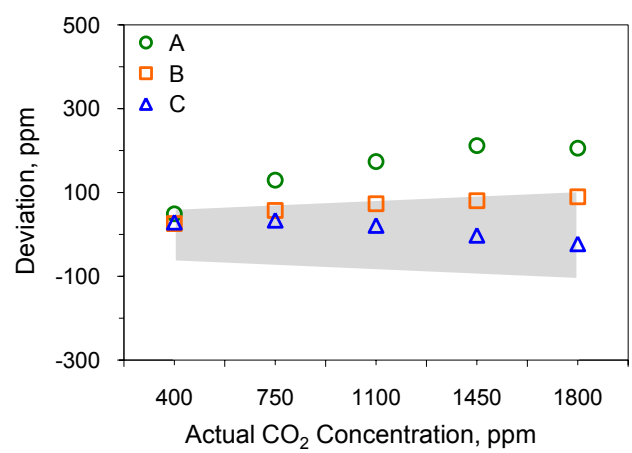
Figure 8. Example of a saturated transmitter.



9a. AirTest Technologies, Model TR9290

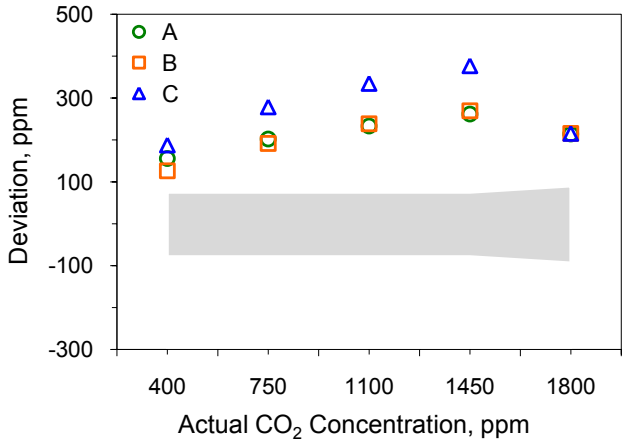


9b. AirTest Technologies, Model EE80-2CT3

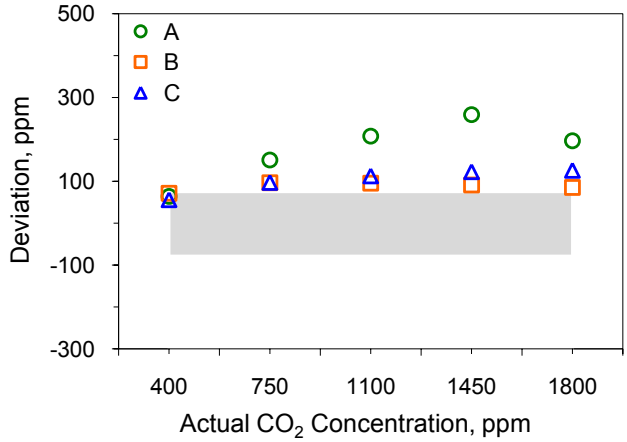


9c. Automation Components Inc, Model ACI/CO_2-VDC-R

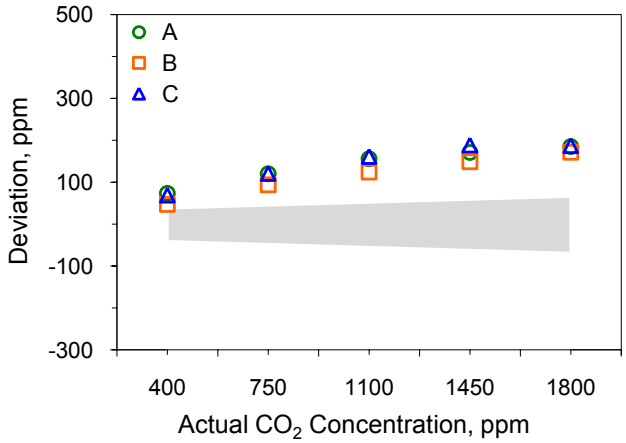
Figure 9. NBCIP measured accuracy of CO_2 transmitters.



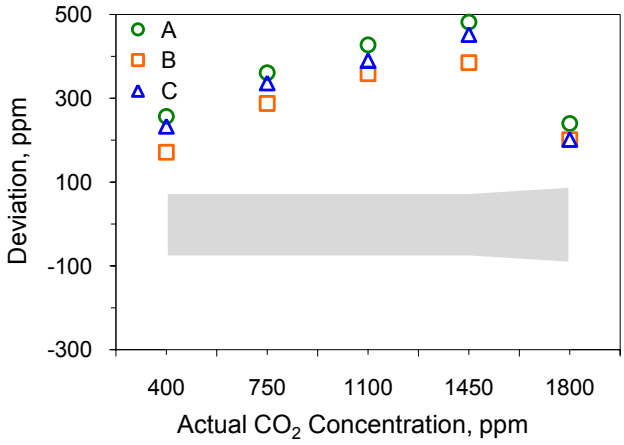
9d. Digital Control Systems Inc, Model AirSense™ M307



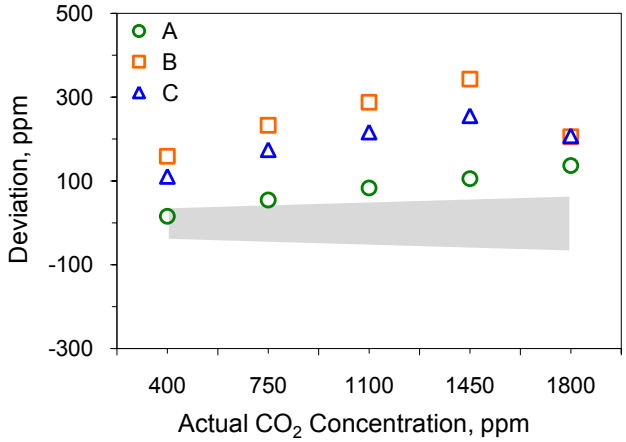
9e. Greystone Energy Systems Inc, Model CDD1A2000



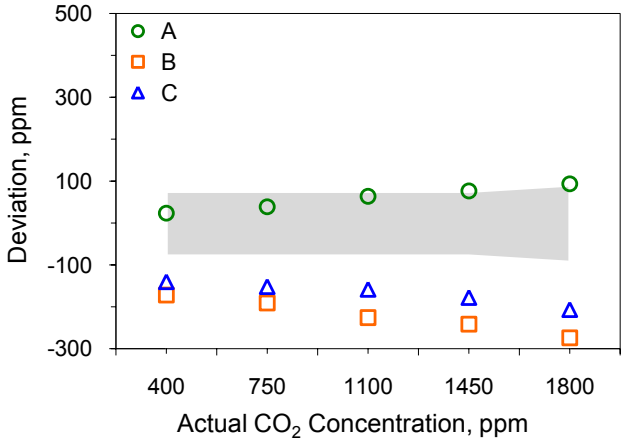
9f. Honeywell, Model C7232A1016



9g. Intec Controls Inc, Model I-310E

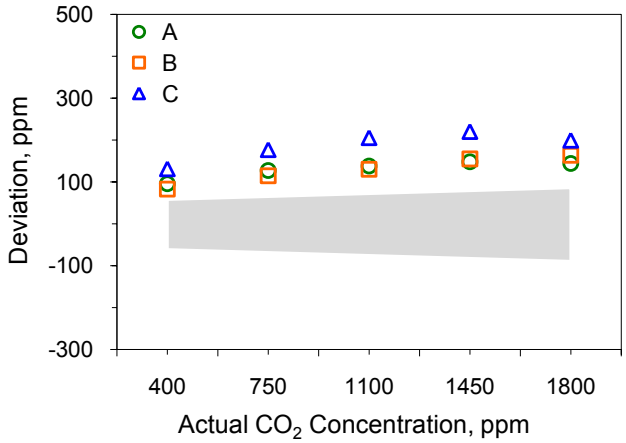


9h. Johnson Controls, Model CD-WA0-00-0

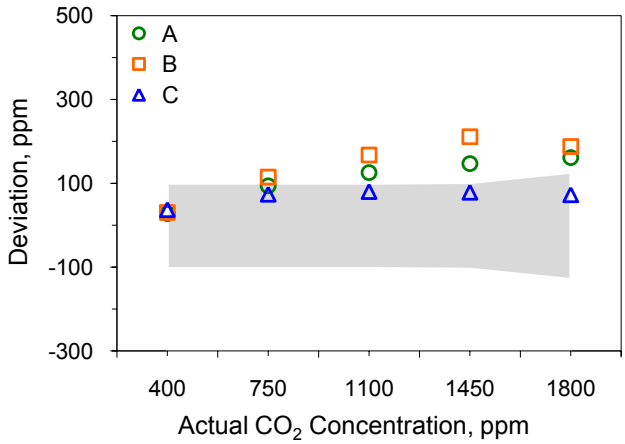


9i. Sensata (Texas Instruments), Model 4GS-1

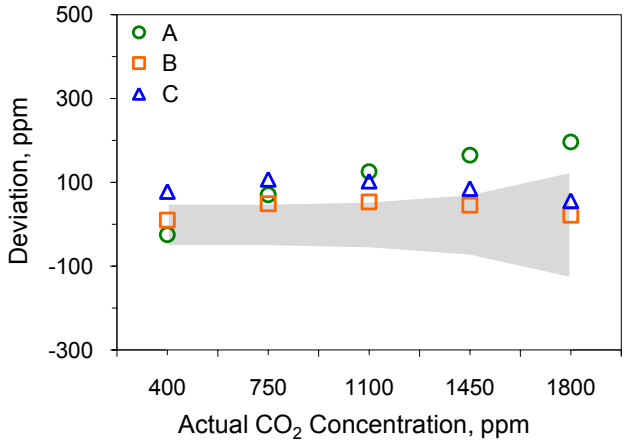
Figure 9. continued NBCIP measured accuracy of CO_2 transmitters.



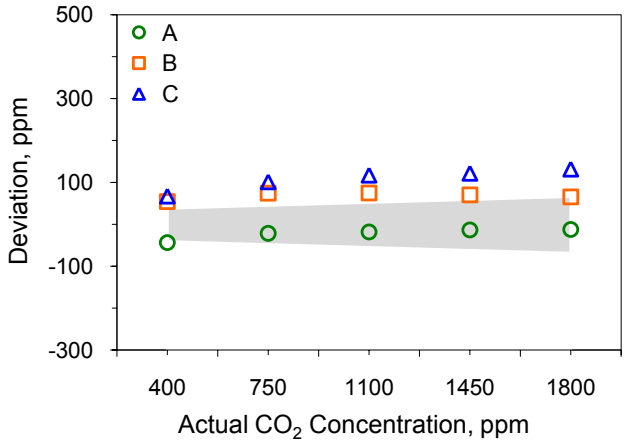
9j. Siemens, Model QPA2000



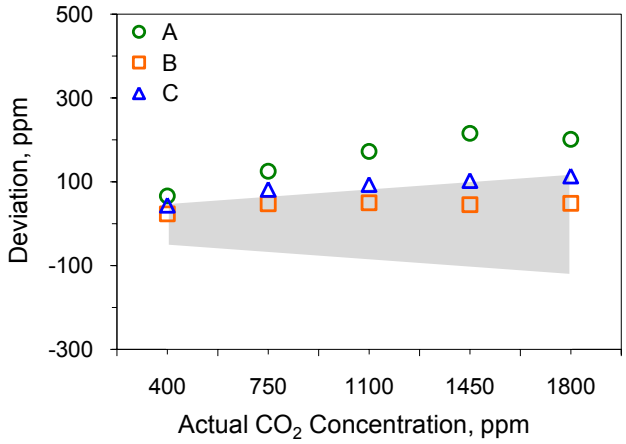
9k. Telaire (GE Sensing), Model Ventostat®8001



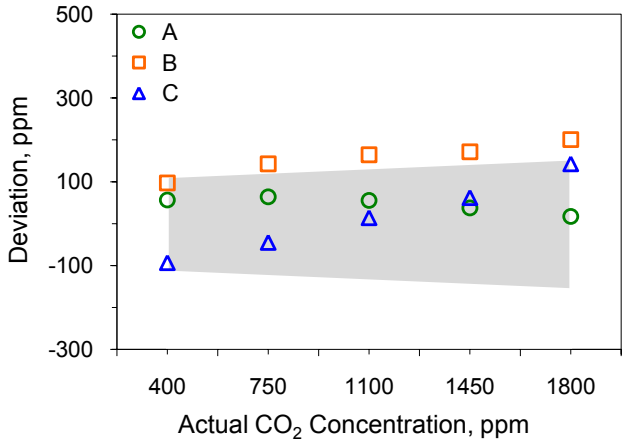
9l. Telaire (GE Sensing), Model Ventostat®8102



9m. Vaisala, Model GMW21



9n. Veris Industries, Model CWE SC



9o. Vulcain, Model 90DM4SM-C-2000

Figure 9. continued NBCIP measured accuracy of CO_2 transmitters.

Table 5. NBCIP test results for accuracy of CO_2 transmitters.

Manufacturer	Model Number	Transmitter	Deviation at, ppm				
			400	750	1100	1450	1800[1]
AirTest Technologies	TR9290	A	47	79	86	96	99
		B	26	59	62	58	49
		C	42	78	91	102	109
AirTest Technologies	EE80-2CT3	A	79	127	158	183	–
		B	85	129	159	195	–
		C	92	126	153	169	185
Automation Components Inc.	ACI/CO2-VDC-R	A	49	129	174	212	–
		B	26	57	73	80	90
		C	29	34	21	–2	–22
Digital Control Systems Inc.	AirSense™ M307	A	156	202	233	262	–
		B	126	192	239	270	–
		C	188	279	335	377	–
Greystone Energy Systems Inc.	CDD1A2000	A	64	151	208	259	–
		B	71	96	95	91	85
		C	56	97	113	123	126
Honeywell	C7232A1016	A	73	120	156	171	185
		B	47	94	124	149	171
		C	69	121	161	188	–
Intec Controls Inc.	I-310E	A	257	361	428	482	–
		B	171	288	359	385	–
		C	233	337	390	452	–
Johnson Controls	CD-WA0-00-0	A	16	55	83	105	137
		B	159	233	288	343	–
		C	111	175	217	256	–
Sensata (Texas Instruments)	4GS-1	A	23	39	64	77	94
		B	–172	–191	–226	–242	–274
		C	–140	–152	–158	–178	–207
Siemens	QPA2000	A	96	127	138	148	144
		B	83	115	130	155	163
		C	131	177	206	220	–
Telaire (GE Sensing)	Ventostat®8001	A	28	94	125	147	161
		B	30	115	167	211	–
		C	37	74	80	79	73
Telaire (GE Sensing)	Ventostat®8002	A	–25	70	126	165	196
		B	10	49	53	45	22
		C	78	107	103	85	56
Vaisala	GMW21	A	–44	–22	–18	–14	–13
		B	54	74	75	70	65
		C	67	101	117	122	131
Veris Industries	CWE SC	A	66	125	172	216	–
		B	23	48	50	45	48
		C	44	82	94	103	114
Vulcain	90DM4SM-C-2000	A	57	64	55	38	17
		B	97	143	164	171	200
		C	–93	–45	14	62	143

[1]*Omitted values in this table correspond to transmitters which are saturated at 1800 ppm.*

Transmitters that utilize an automatic baseline adjustment use a manufacturer specific proprietary algorithm to periodically adjust the baseline CO_2 concentration. For many transmitters that use this method, it appears that a baseline value of 400 ppm is set when the transmitter "reads" a low level of CO_2 over some extended period of time. Prior to placing the transmitters in the test chamber for testing, all transmitters are operating in the environment of the laboratory where the barometric pressure is approximately 14.2 psia (97.91 kPa) (due to the 960 feet elevation at the location of testing). The ambient CO_2 concentration (during unoccupied periods) is approximately 350-380 ppm (outdoor air CO_2 concentrations vary on a daily basis). Operating in the laboratory environment for an extended period of time has allowed these transmitters to "adjust" their baseline; therefore, when these transmitters are placed under test conditions and compared to "actual" CO_2 concentration levels, there is some bias in the measured value reported by the transmitter. Because this bias is unknown, there is no attempt by NBCIP to compensate for it when showing the test results. This issue is further discussed in the conclusions section.

All models tested are factory scaled to provide 0-10 VDC output for CO_2 concentration levels between 0 and 2,000 ppm. (The exception is for the Honeywell transmitter which has an output of 4–20mA.) All transmitters were tested under "as received" conditions from the supplier. That is, no calibration was performed on the transmitters prior to testing. For some transmitters, the test results show that the transmitters did not follow the assumed scaling. This is evident by the large departure from a non-zero slope of the data points. Table 5 shows the numerical values of the deviations for each transmitter at each CO_2 level. Data values corresponding to saturated transmitter output are not included in the table.

Repeatability

Repeatability is the degree to which a CO_2 transmitter produces the same measurement when subjected repeatedly to the same conditions as they are approached from the same direction. Figure 10 illustrates the error associated with the repeatability tests. The error is defined as the difference between the two forward measurements at CO_2 concentrations of 750 ppm,1100 ppm, and 1450 ppm. The repeatability test results for all transmitters are summarized in Table 6.

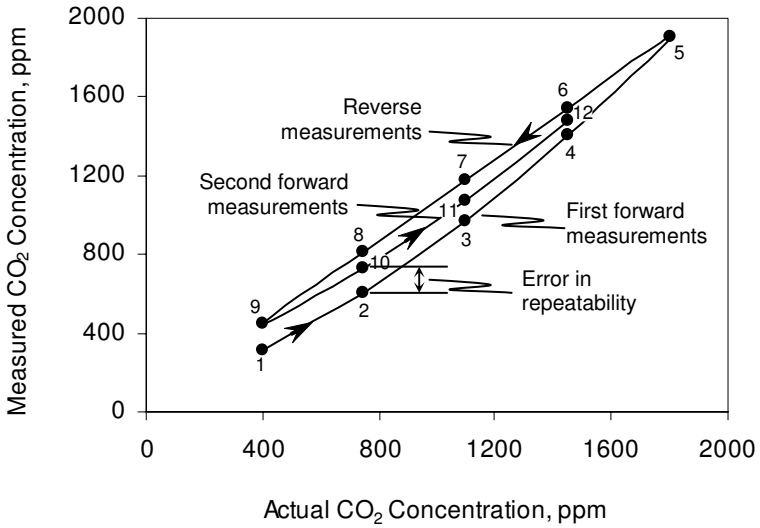


Figure 10. Example of repeatability of a carbon dioxide transmitter. NBCIP evaluated repeatability at 750, 1100, and 1450 ppm CO_2, corresponding to the difference in value between data points 2 and 10, 3 and 11, aand 4 and 12, respectively.

Table 6. NBCIP test results for repeatability of CO_2 transmitters at 750, 1100, and 1450 ppm CO_2.

Manufacturer	Model Number	Transmitter	Error in Repeatability, ppm			Max Error (Transmitter)	Max Error (Model)
			750 ppm	1100 ppm	1450 ppm		
AirTest Technologies	TR9290	A	1	0	0	1	7
		B	6	5	7	7	
		C	4	4	6	6	
AirTest Technologies	EE80-2CT3	A	3	3	3	3	12
		B	0	2	7	7	
		C	12	6	7	12	
Automation Components Inc.	ACI/CO2-VDC-R	A	1	2	5	5	5
		B	2	3	4	4	
		C	2	4	2	4	
Digital Control Systems Inc.	AirSense™ M307	A	2	7	0	7	7
		B	3	6	5	6	
		C	3	3	4	4	
Greystone Energy Systems Inc.	CDD1A2000	A	2	5	7	7	10
		B	4	10	7	10	
		C	1	5	2	5	
Honeywell	C7232A1016	A	2	3	11	11	11
		B	5	6	7	7	
		C	7	7	1	7	
Intec Controls Inc.	I-310E	A	8	7	14	14	14
		B	1	4	9	9	
		C	3	6	3	3	
Johnson Controls	CD-WA0-00-0	A	8	6	11	11	11
		B	3	8	3	8	
		C	0	0	5	5	
Sensata (Texas Instruments)	4GS-1	A	3	4	2	4	6
		B	0	6	1	6	
		C	0	1	0	1	
Siemens	QPA2000	A	2	2	2	2	25
		B	19	25	0	25	
		C	14	11	6	14	
Telaire (GE Sensing)	Ventostat®8001	A	3	2	5	5	5
		B	1	4	2	4	
		C	1	1	4	4	
Telaire (GE Sensing)	Ventostat®8002	A	3	4	2	4	4
		B	2	2	2	2	
		C	1	2	1	2	
Vaisala	GMW21	A	0	4	7	7	8
		B	1	3	2	3	
		C	1	5	8	8	
Veris Industries	CWE SC	A	2	4	6	6	7
		B	7	5	4	7	
		C	5	3	0	5	
Vulcain	90DM4SM-C-2000	A	0	0	5	5	10
		B	3	1	6	6	
		C	6	5	10	10	

Note: Only the magnitude of the error in repeatability is shown in the table; consequently, negative signs have been omitted.

Linearity

Linearity is the extent to which the CO_2 transmitter input and output can be approximated by a linear function. NBCIP assessed the error in linearity of the CO_2, transmitters as the maximum difference between measured CO_2 concentrations and a linear-least squares regression of the measured values. Two types of regression analysis were performed on the measured values. Regression Method 1 is a linear regression of the data alone. In this analysis, the regression line may or may not pass through the origin. Regression Method 2 is a linear regression of the data with the regression line being forced to pass through the origin. Figure 11 illustrates this concept. In the figure, Regression Line 1 represents a least-squares regression of the data point without forcing the regression analysis to pass through the origin. Regression Line 2 is a least-squares regression where the analysis is forced to pass through the origin. As seen in the figure, different errors exist between a particular datum point and the two regression lines. Regression Method 2 is representative of the linearity error that would result from scaling the transmitter output of 0 and 10 VDC to correspond with the transmitter range of 0 to 2000 ppm.

The maximum difference between measured CO_2 concentrations and the two linear regression methods are summarized in Table 7. The linear regression plots for all transmitters are provided in Appendix D. Each plot in the appendix shows the measured data, the regression line, the regression formula and the R^2-value for the three transmitters of a given model. The R^2-value is the residual error between the regression line and the data points. A value of 1 indicates a regression line with no residual error. Data values at 1800 ppm were not included in the regression analysis for those transmitters which exhibited saturation at this CO_2 concentration.

The linearity results based on the regression method which does not force the regression analysis to pass through the origin show that the majority of the transmitters have linearity values less than 15 ppm. Thus indicates that transmitters can be accurately characterized by a linear relationship over the CO_2 concentration range from 400 ppm to 1800 ppm.

The linearity results based on the regression method which forces the regression analysis to pass through the origin are not as good. For some transmitters, the results are nearly the same for the first regression method. However, for other transmitters the linearity values are as high as 109 ppm. These results suggest that assuming a transmitter's reading would be zero when it is exposed to a 0 ppm CO_2 concentration gas (such as nitrogen) may lead to inaccurate results. When calibrating transmitters in the field, it is recommended that at least two CO_2 concentrations be used to verify the transmitter's response.

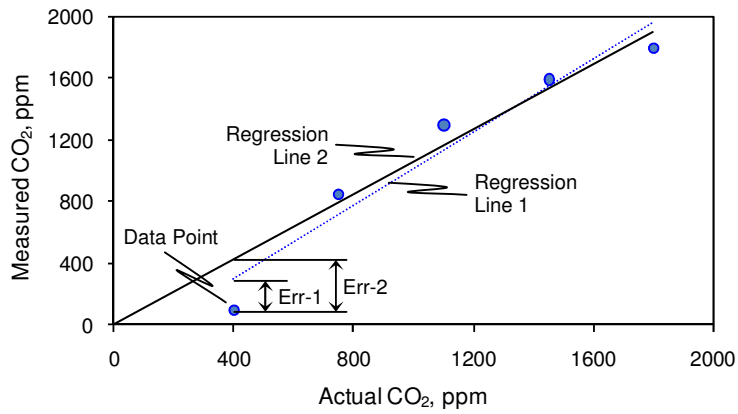


Figure 11. Illustration of linearity error of a CO_2 transmitter.

Table 7. NBCIP test results for error in linearity of CO_2 transmitters.

Manufacturer	Model Number	Transmitter	Regression Method 1		Regression Method 2	
			Linearity Error (Transmitter)	Linearity Error (Model)	Linearity Error (Transmitter)	Linearity Error (Model)
AirTest Technologies	TR9290	A	10	16	29	29
		B	16		28	
		C	11		24	
AirTest Technologies	EE80-2CT3	A	7	8	23	43
		B	5		27	
		C	8		43	
Automation Components Inc.	ACI/CO2-VDC-R	A	15	15	15	32
		B	9		15	
		C	11		32	
Digital Control Systems Inc.	AirSense™ M307	A	6	15	71	71
		B	9		42	
		C	15		69	
Greystone Energy Systems Inc.	CDD1A2000	A	12	14	13	46
		B	12		46	
		C	14		33	
Honeywell	C7232A1016	A	15	15	31	31
		B	9		16	
		C	7		16	
Intec Controls Inc.	I-310E	A	16	25	104	104
		B	25		60	
		C	18		92	
Johnson Controls	CD-WA0-00-0	A	5	9	14	55
		B	8		55	
		C	9		33	
Sensata (Texas Instruments)	4GS-1	A	5	9	5	100
		B	5		100	
		C	9		87	
Siemens	QPA2000	A	11	11	54	59
		B	6		40	
		C	8		59	
Telaire (GE Sensing)	Ventostat®8001	A	19	19	19	32
		B	14		28	
		C	16		32	
Telaire (GE Sensing)	Ventostat®8002	A	24	24	67	67
		B	22		29	
		C	21		61	
Vaisala	GMW21	A	8	11	38	38
		B	10		35	
		C	11		35	
Veris Industries	CWE SC	A	5	11	9	27
		B	10		21	
		C	11		27	
Vulcain	90DM4SM-C-2000	A	11	12	45	109
		B	11		46	
		C	12		109	

Note: Only the magnitude of the error in linearity is shown in the table; consequently, negative signs have been omitted.

Hysteresis

Hysteresis is the error in measurement when the same CO_2 concentration condition is approached from a lower and then a higher concentration condition. NBCIP assessed the hysteresis of each transmitter using the forward measurement and the reverse measurement for the CO_2 concentrations of 750, 1100, and 1450 ppm. Figure 12 illustrates the data points used to calculate the hysteresis error for each transmitter. The hysteresis test results for all transmitters are summarized in Table 8. With few exceptions, all transmitters have a hysteresis less than 13 ppm.

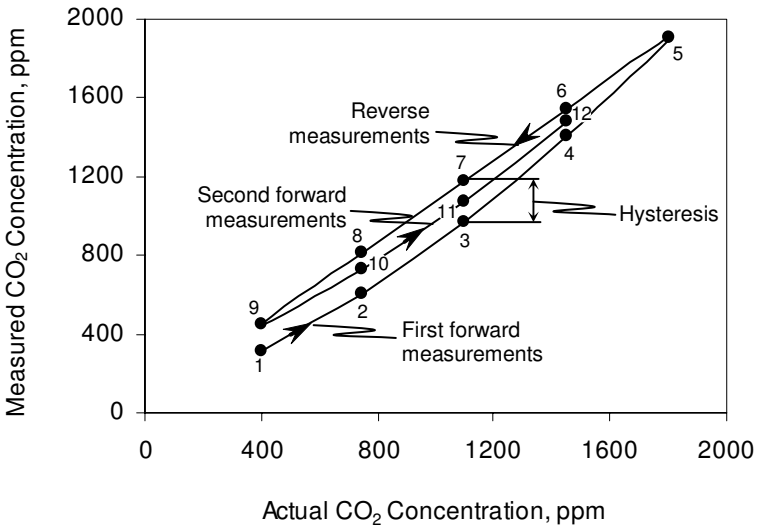


Figure 12. Example of hysteresis of a CO_2 transmitter. NBCIP evaluated hysteresis at 750, 1100, and 1450 ppm CO_2, corresponding to the difference in value between points 2 and 8, 3 and 7, and 4 and 6, respectively.

Table 8. NBCIP test results for hysteresis of CO_2 transmitters at 750, 1100, and 1450 ppm CO_2.

Manufacturer	Model Number	Transmitter	Hysteresis, ppm			Max Error (Transmitter)	Max Error (Model)
			750 ppm	1100 ppm	1450 ppm		
AirTest Technologies	TR9290	A	3	1	3	3	3
		B	0	1	3	3	
		C	3	1	1	3	
AirTest Technologies	EE80-2CT3	A	9	12	6	12	13
		B	12	2	1	12	
		C	13	8	8	13	
Automation Components Inc.	ACI/CO2-VDC-R	A	4	2	1	4	9
		B	6	9	2	9	
		C	3	1	2	3	
Digital Control Systems Inc.	AirSense™ M307	A	1	1	0	1	7
		B	7	6	3	7	
		C	5	4	3	5	
Greystone Energy Systems Inc.	CDD1A2000	A	3	4	2	4	6
		B	6	6	2	6	
		C	4	1	1	4	
Honeywell	C7232A1016	A	4	5	6	6	6
		B	1	0	5	5	
		C	0	6	1	6	
Intec Controls Inc.	I-310E	A	11	3	1	11	11
		B	4	9	3	9	
		C	2	7	1	7	
Johnson Controls	CD-WA0-00-0	A	12	7	10	12	12
		B	4	7	2	7	
		C	6	7	7	7	
Sensata (Texas Instruments)	4GS-1	A	4	1	3	4	6
		B	3	6	1	6	
		C	4	1	3	4	
Siemens	QPA2000	A	4	2	5	5	31
		B	23	31	2	31	
		C	10	15	10	15	
Telaire (GE Sensing)	Ventostat®8001	A	6	3	4	6	6
		B	5	6	2	6	
		C	5	4	4	5	
Telaire (GE Sensing)	Ventostat®8002	A	5	0	6	6	6
		B	3	2	1	3	
		C	4	3	6	6	
Vaisala	GMW21	A	3	5	6	6	10
		B	2	3	3	3	
		C	8	5	10	10	
Veris Industries	CWE SC	A	7	3	4	7	7
		B	3	1	2	3	
		C	0	0	3	3	
Vulcain	90DM4SM-C-2000	A	6	6	4	6	18
		B	3	8	8	8	
		C	4	18	7	18	

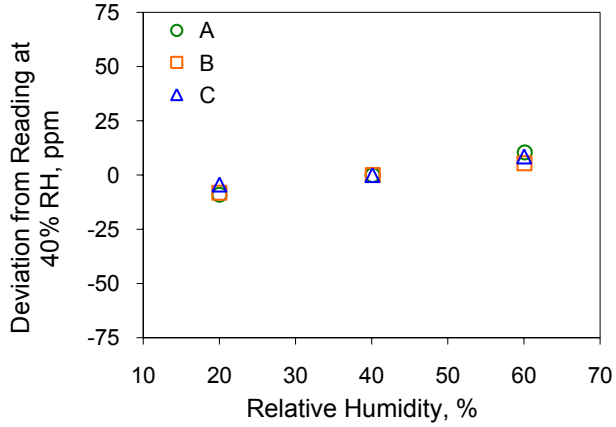
Note: Only the magnitude of the hysteresis is shown in the table; consequently, negative signs have been omitted.

Humidity Sensitivity

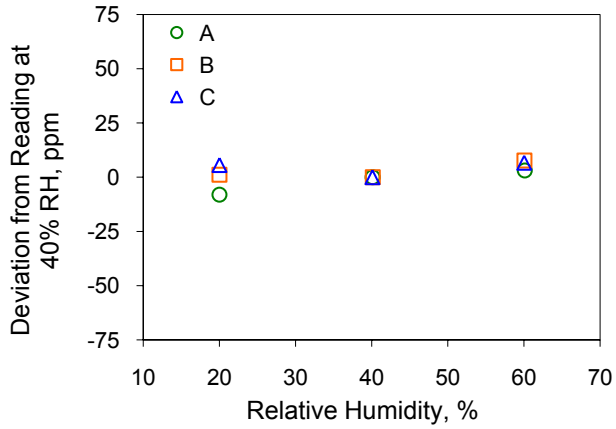
Although none of the CO_2 transmitter manufacturers report any humidity sensitivity on the performance of their transmitters, NBCIP performed tests to determine the sensitivity of the CO_2 transmitters to changes in humidity. The effect of humidity on CO_2 transmitters was evaluated by varying the relative humidity in the test chamber while maintaining the chamber CO_2 concentration at 1100 ppm, temperature at 73°F (22.8°C), and pressure at 14.7 psia (101.35 kPa). 40% relative humidity was used as the reference relative humidity. Transmitter readings were taken at 20%, 40% and 60% relative humidity. The deviation in transmitter readings was calculated from the difference of the transmitter readings at the 20% and 60% relative humidity and the transmitter reading at 40% relative humidity. These results are shown in Figure 13.

The humidity sensitivity of each CO_2 transmitter was calculated using a linear regression of the test results. The slope of the regression line represents the sensitivity of the transmitter in terms of deviation in ppm reading per % change in relative humidity. The sensitivity results are summarized in Table 9.

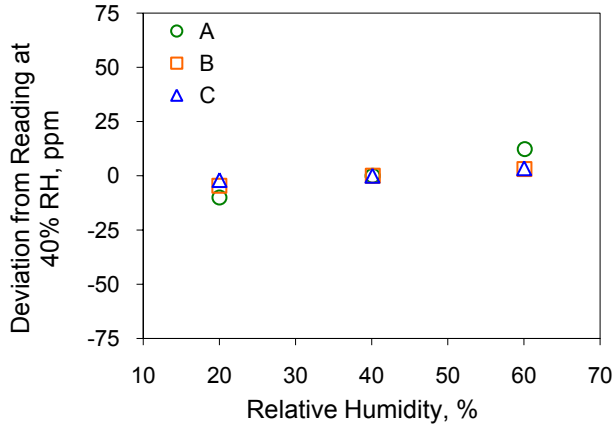
All transmitters show some dependence on humidity; although, for most, the affect is small. However, some transmitters show a very strong dependence on humidity (refer to Figures 13d, 13g and 13l). For the transmitter in Figure 13l, the dependence was not consistent for the three transmitters of the same model. This suggests that there may have been a change in the manufacturing process or materials used in manufacturing these transmitters between the lots from which the transmitters were purchased by NBCIP.



13a. AirTest Technologies, Model TR9290

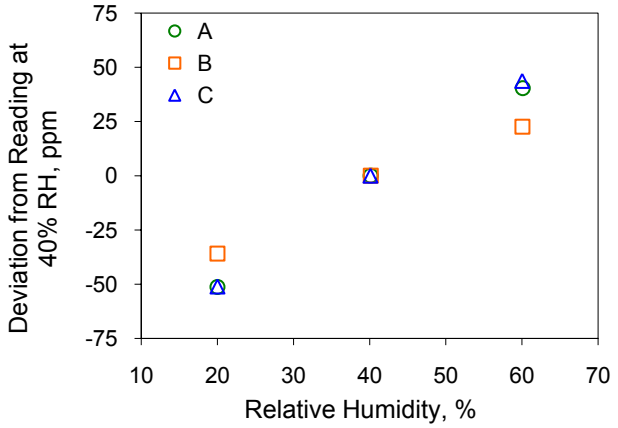


13b. AirTest Technologies, Model EE80-2CT3

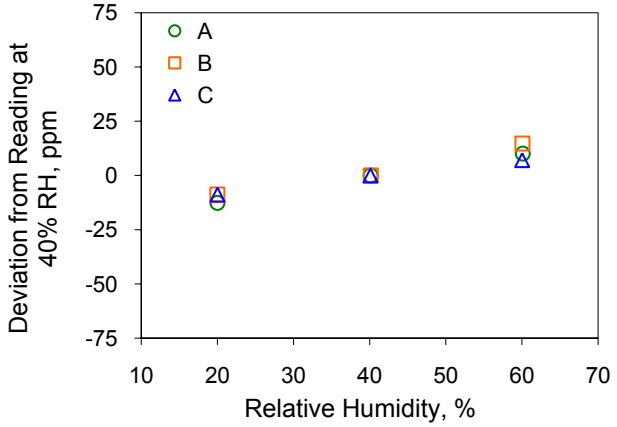


13c. Automation Components Inc, Model ACI/CO2-VDC-R

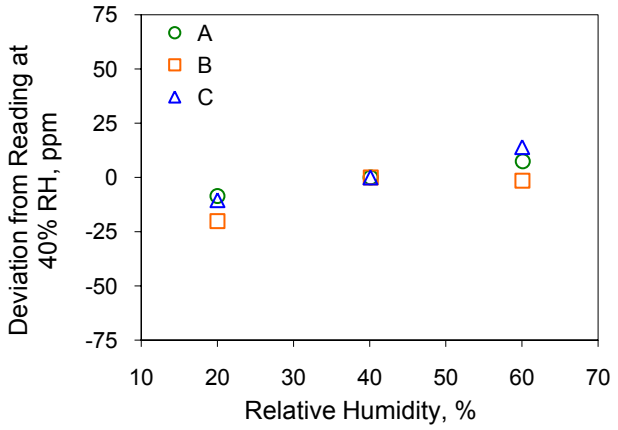
Figure 13. NBCIP measured humidity sensitivity of CO_2 transmitters.



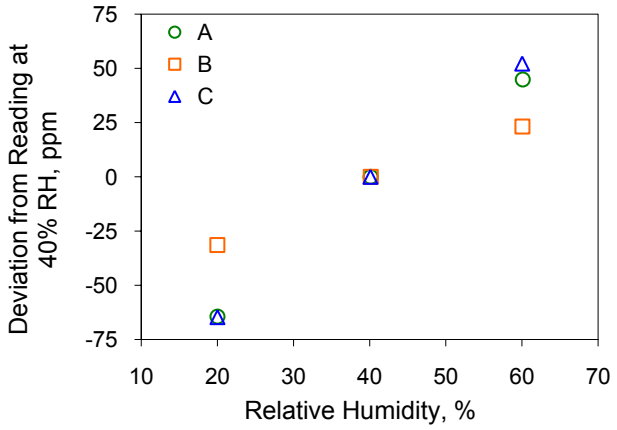
13d. Digital Control Systems Inc, Model AirSense™ M307



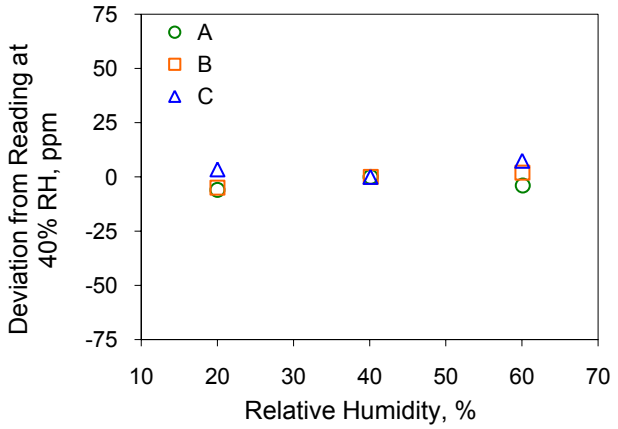
13e. Greystone Energy Systems Inc, Model CDD1A2000



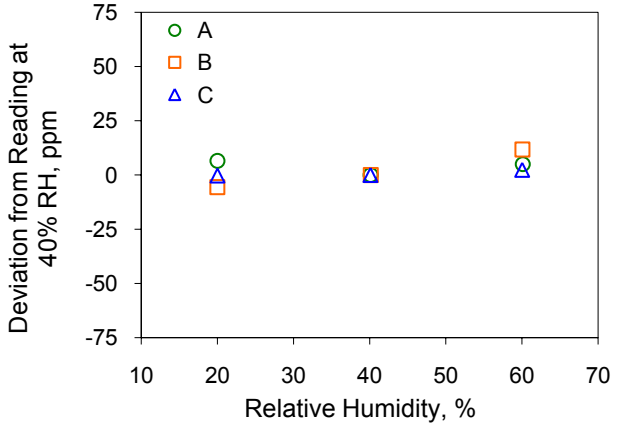
13f. Honeywell, Model C7232A1016



13g. Intec Controls Inc, Model I-310E

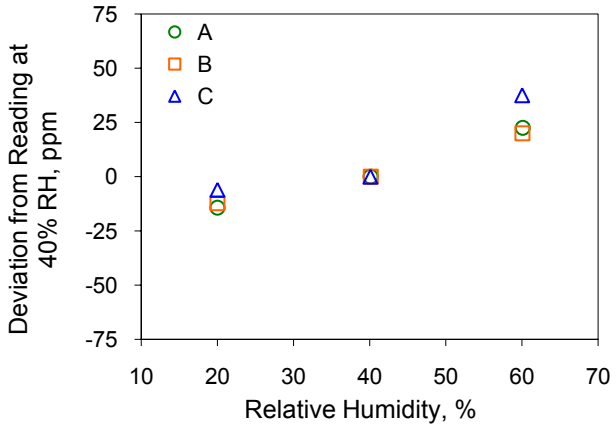


13h. Johnson Controls, Model CD-WA0-00-0

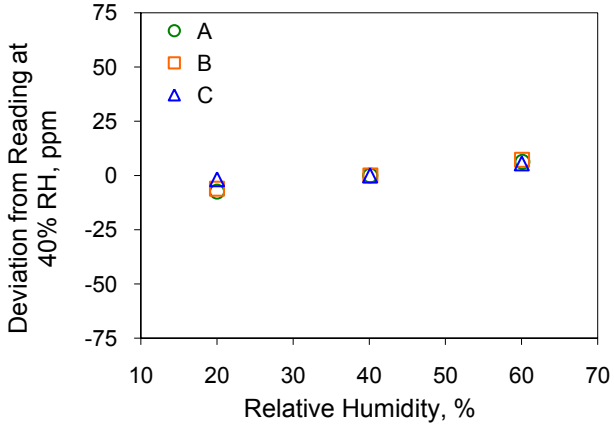


13i. Sensata (Texas Instruments) Model 4GS-1

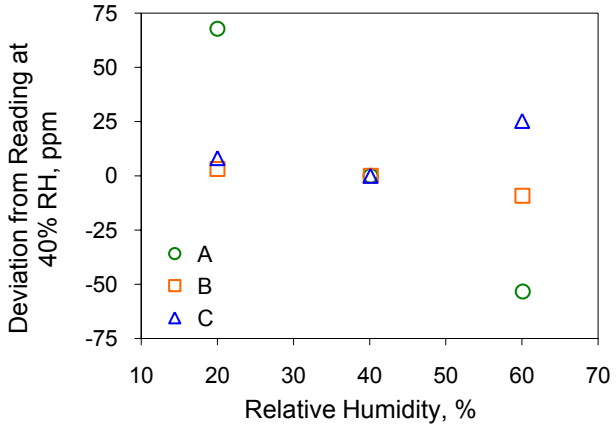
Figure 13. (continued) NBCIP measured humidity sensitivity of CO_2 transmitters.



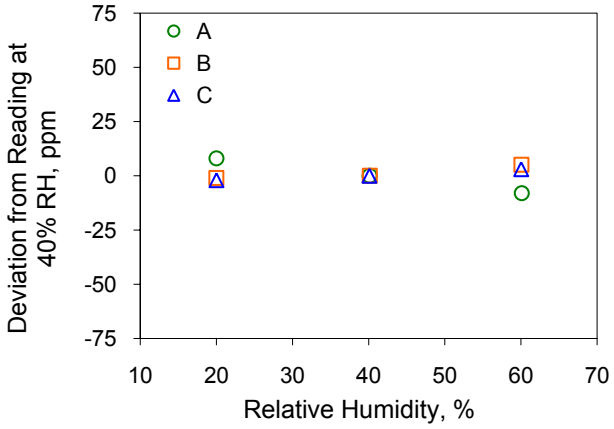
13j. Siemens, Model QPA2000



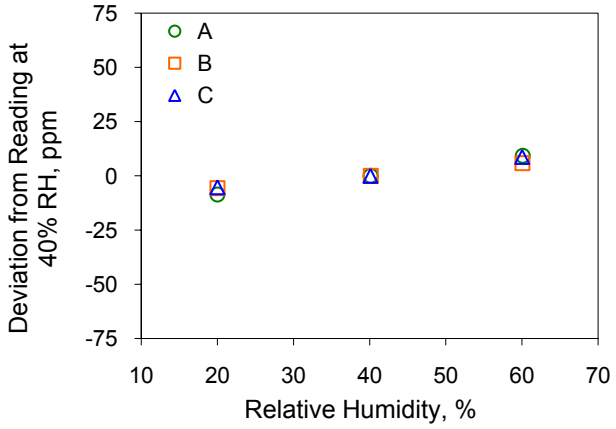
13k. Telaire (GE Sensing), Model Ventostat®8001



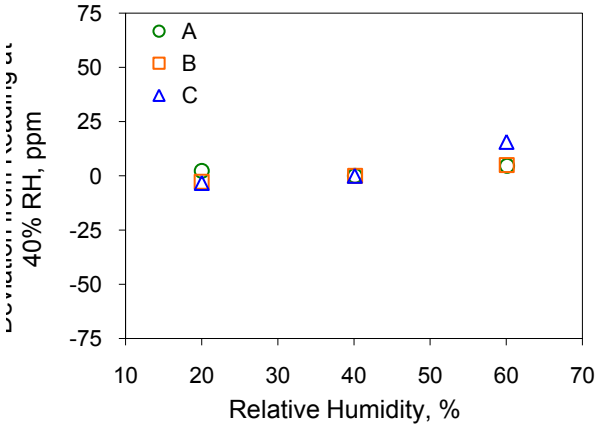
13l. Telaire (GE Sensing), Model Ventostat®8102



13m. Vaisala, Model GMW21



13n. Veris Industries, Model CW ESC



13o. Vulcain, Model 90DM4SM-C-2000

Figure 13. (continued) NBCIP measured humidity sensitivity of CO_2 transmitters.

Table 9. NBCIP test results for humidity sensitivity of CO_2 transmitters.

Manufacturer	Model Number	Transmitter	Reading at			Sensitivity, ppm/ %RH
			20% RH, ppm	40% RH, ppm	60% RH, ppm	
AirTest Technologies	TR9290	A	1192	1201	1212	0.5
		B	1195	1203	1209	0.3
		C	1212	1217	1225	0.3
AirTest Technologies	EE80-2CT3	A	1239	1247	1251	0.3
		B	1258	1257	1264	0.2
		C	1301	1295	1302	0.0
Automation Components Inc.	ACI/CO2-VDC-R	A	1273	1283	1295	0.6
		B	1176	1181	1184	0.2
		C	1125	1127	1130	0.1
Digital Control Systems Inc.	AirSense™ M307	A	1282	1333	1373	2.3
		B	1300	1335	1358	1.5
		C	1363	1414	1458	2.4
Greystone Energy Systems Inc.	CDD1A2000	A	1296	1309	1319	0.6
		B	1178	1187	1202	0.6
		C	1211	1219	1226	0.4
Honeywell	C7232A1016	A	1255	1263	1271	0.4
		B	1262	1282	1281	0.5
		C	1303	1314	1328	0.6
Intec Controls Inc.	I-310E	A	1448	1513	1557	2.7
		B	1420	1451	1474	1.4
		C	1422	1487	1539	2.9
Johnson Controls	CD-WA0-00-0	A	1185	1191	1187	0.1
		B	1386	1391	1393	0.2
		C	1316	1313	1320	0.1
Sensata (Texas Instruments)	4GS-1	A	1174	1167	1172	0.0
		B	870	876	887	0.4
		C	942	943	945	0.1
Siemens	QPA2000	A	1209	1223	1246	0.9
		B	1218	1230	1250	0.8
		C	1285	1291	1329	1.1
Telaire (GE Sensing)	Ventostat®8001	A	1222	1229	1236	0.3
		B	1271	1277	1284	0.3
		C	1177	1179	1185	0.2
Telaire (GE Sensing)	Ventostat®8002	A	1368	1300	1246	–3.0
		B	1172	1169	1160	–0.3
		C	1177	1169	1195	0.4
Vaisala	GMW21	A	1096	1088	1080	–0.4
		B	1174	1175	1180	0.2
		C	1213	1215	1218	0.1
Veris Industries	CWE SC	A	1275	1283	1293	0.4
		B	1200	1205	1211	0.3
		C	1222	1227	1236	0.3
Vulcain	90DM4SM-C-2000	A	1163	1161	1165	0.1
		B	1261	1264	1269	0.2
		C	1073	1077	1092	0.5

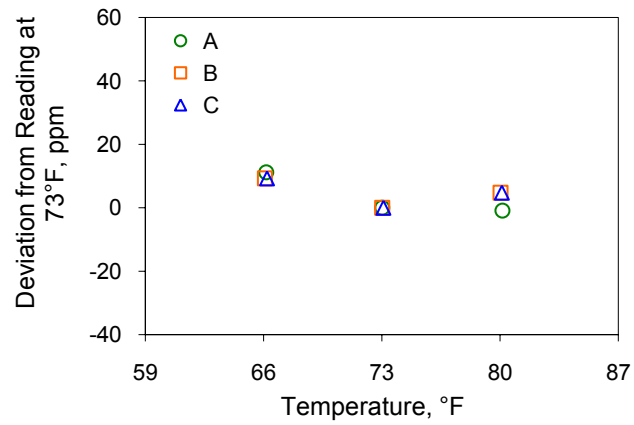
Temperature Sensitivity

From the manufacturer data, as summarized in Table 1, eight of the fifteen CO_2 transmitter models state the dependency of temperature on the transmitter output. The remaining seven transmitter models do not specify any temperature dependency.

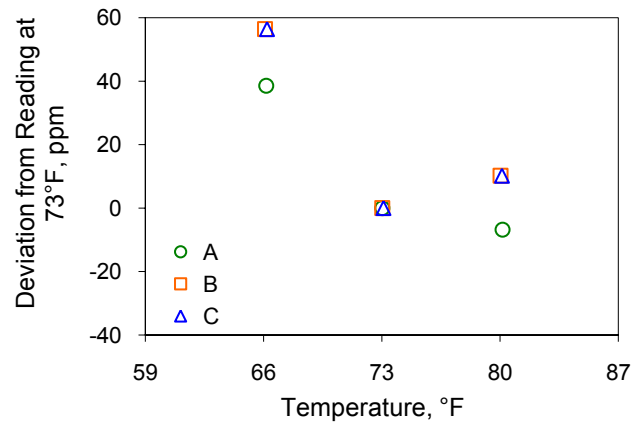
The effect of temperature on CO_2 transmitters was evaluated by varying the temperature in the test chamber while maintaining the chamber CO_2 concentration at 1100 ppm, an absolute humidity of 0.0069 lbm_v/lbm_a (kg_v/kg_a) and a pressure of 14.7 psia (101.35 kPa). 73 °F (22.8 °C) was used as the reference temperature. Transmitter readings were taken at temperature of 66°F (18.9 °C), 73 °F (22.8 °C) and 80 °F (26.7 °C). The deviation in transmitter readings was calculated from the difference of the transmitter readings at temperatures of 66 °F (18.9 °C) and 80 °F (26.7 °C) and the transmitter reading at 73 °F (22.8 °C). These results are shown in Figure 14.

The temperature sensitivity of each CO_2 transmitter was calculated using a linear regression of the test results. The slope of the regression line represents the sensitivity of the transmitter in terms of deviation in ppm reading per degree change in temperature. The numerical results of the transmitter readings at each of the test conditions along with the calculated sensitivity are summarized in Table 10.

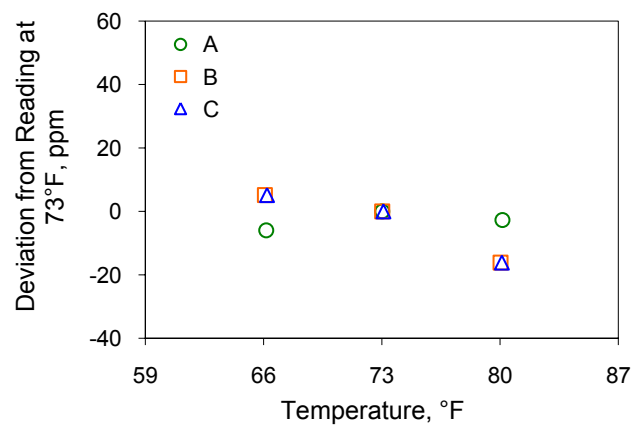
For many of the transmitters, the temperature sensitivity is negligibly small. Nine transmitter models showed temperature sensitivity within 5 ppm/1.8 °F (5 ppm/ °C). Transmitter B from AirTest Technologies Model EE80 showed the highest temperature sensitivity of 10 ppm increase in transmitter reading per 1.8 °F (1 °C) decrease in temperature.



14a. AirTest Technologies, Model TR9290

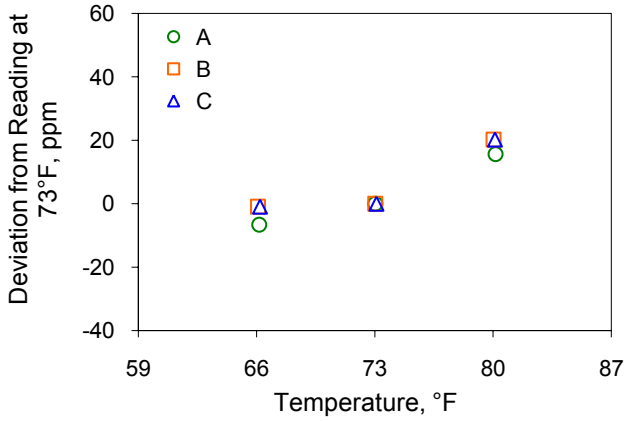


14b. AirTest Technologies, Model EE80-2CT3

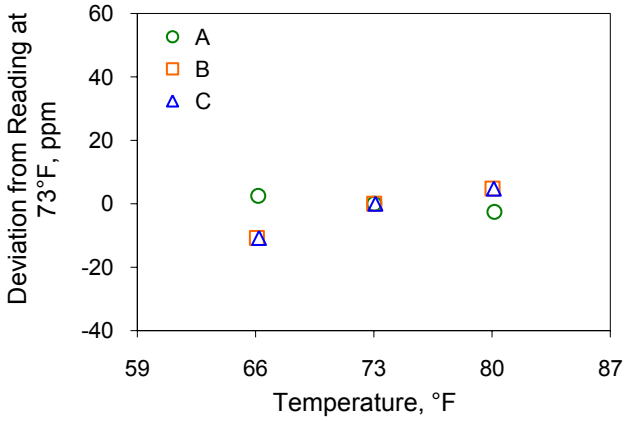


14c. Automation Components Inc., Model ACI/CO2-VDC-R

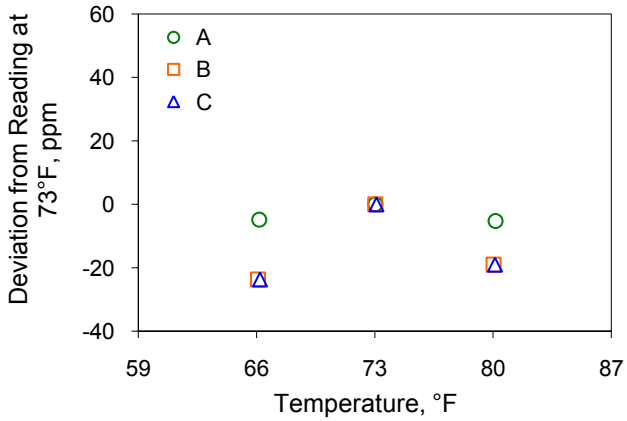
Figure 14. NBCIP measured temperature sensitivity of CO_2 transmitters.



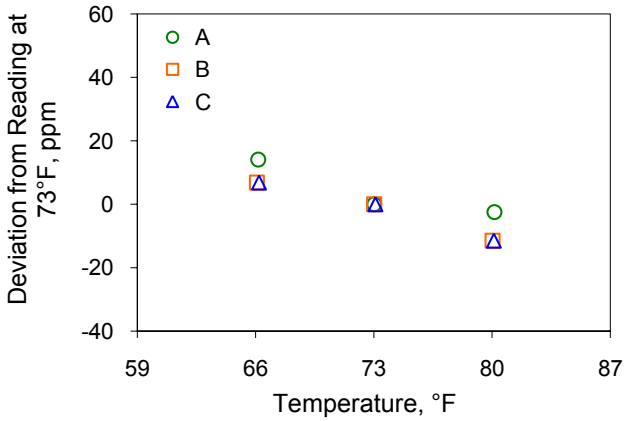
14d. Digital Control Systems Inc., Model AirSense™ M307



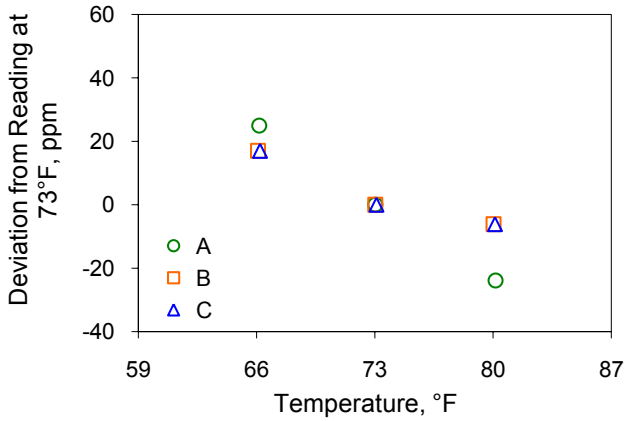
14e. Greystone Energy Systems Inc, Model CDD1A2000



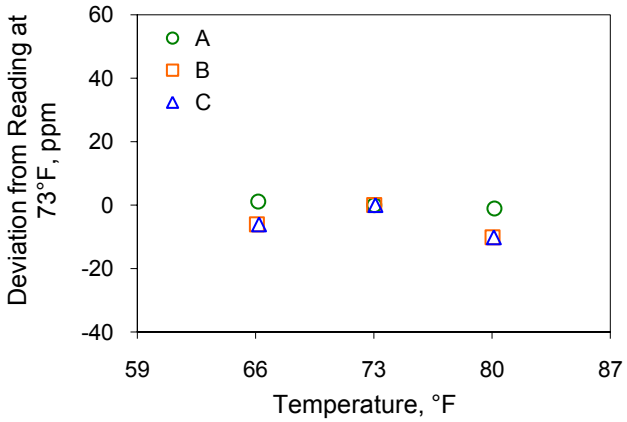
14f. Honeywell, Model C7232A1016



14g. Intec Controls Inc, Model I-310E

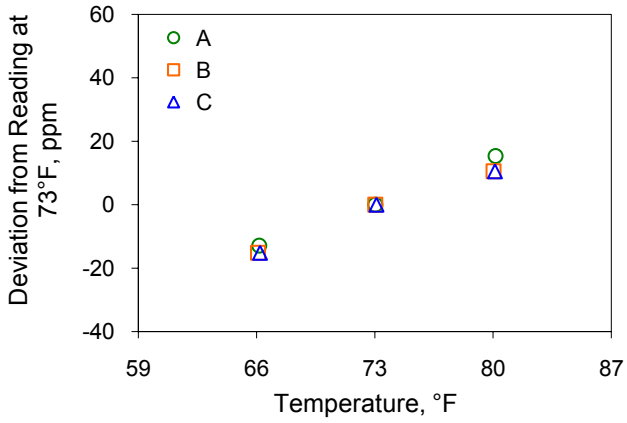


14h. Johnson Controls, Model CD-WA0-00-0

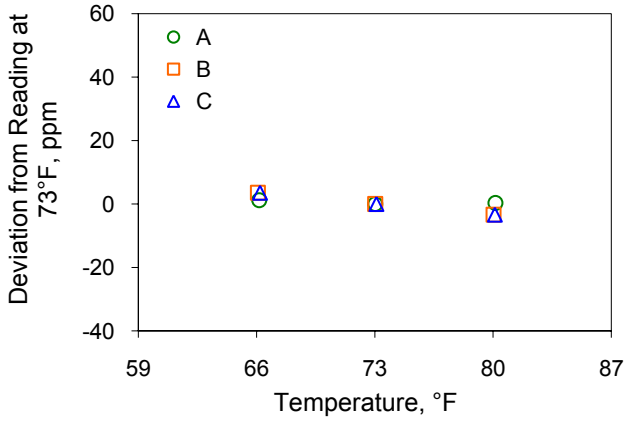


14i. Sensata (Texas Instruments), Model 4GS-1

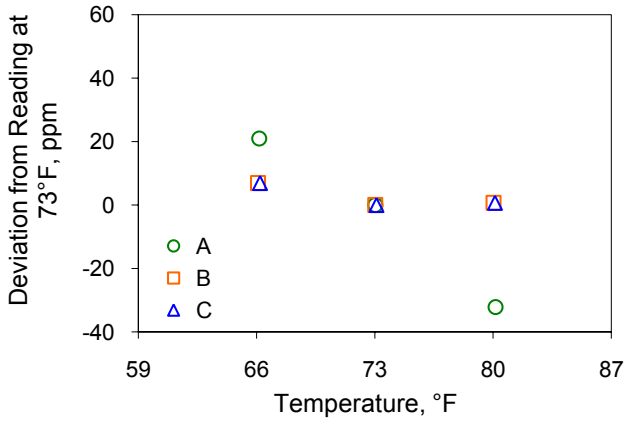
Figure 14. (continued) NBCIP measured temperature sensitivity of CO_2 transmitters.



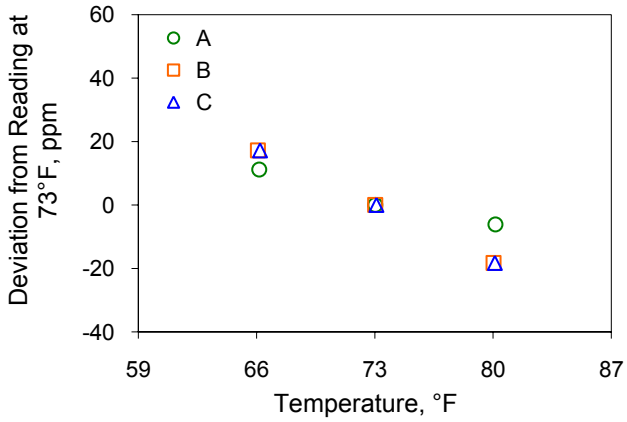
14j. Siemens, Model QPA2000



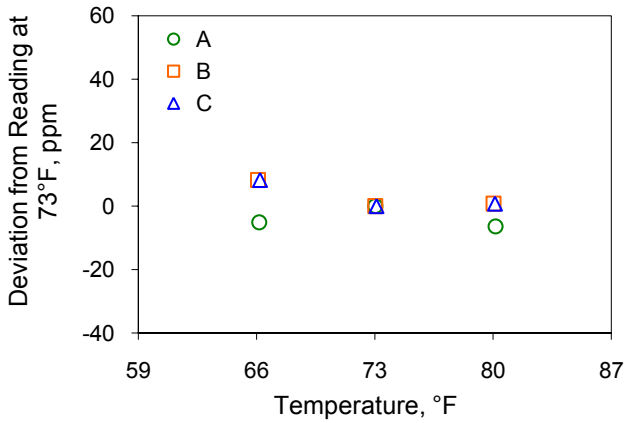
14k. Telaire (GE Sensing), Model Ventostat®8001



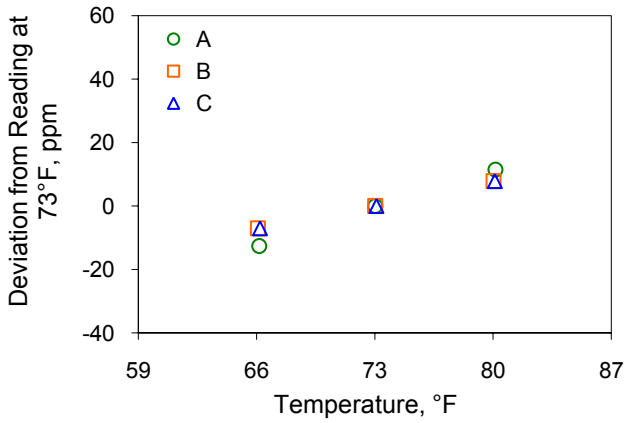
14l. Telaire (GE Sensing), Model Ventostat®8102



14m. Vaisala, Model GMW21



14n. Veris Industries, Model CWE SC



14o. Vulcain, Model 90DM4SM-C-2000

Figure 14. (continued) NBCIP measured temperature sensitivity of CO_2 transmitters.

Table 10. NBCIP test results for temperature sensitivity of CO_2 transmitters.

Manufacturer	Model Number	Transmitter	Reading at			Temperature Sensitivity, ppm / 1.8°F (ppm/ °C)	
			66°F (18.9°C), ppm	73°F (22.8°C), ppm	80°F (26.7°C), ppm	Calculated	Manufacturer Specified
AirTest Technologies	TR9290	A	1194	1183	1182	−2	5
		B	1156	1150	1153	0	
		C	1187	1177	1182	−1	
AirTest Technologies	EE80-2CT3	A	1298	1259	1252	−6	5
		B	1295	1231	1219	−10	
		C	1305	1248	1259	6	
Automation Components Inc.	ACI/CO2-VDC-R	A	1271	1277	1274	0	3[1]
		B	1163	1171	1178	2	
		C	1120	1115	1099	−3	
Digital Control Systems Inc.	AirSense™ M307	A	1331	1337	1353	3	NA
		B	1316	1346	1382	9	
		C	1438	1439	1459	3	
Greystone Energy Systems Inc.	CDD1A2000	A	1314	1312	1309	−1	4[1]
		B	1219	1206	1199	−3	
		C	1204	1215	1220	2	
Honeywell	C7232A1016	A	1238	1243	1238	0	NA
		B	1202	1214	1203	0	
		C	1228	1252	1233	1	
Intec Controls Inc.	I-310E	A	1551	1537	1534	−2	NA
		B	1432	1462	1491	8	
		C	1499	1492	1481	−2	
Johnson Controls	CD-WA0-00-0	A	1210	1185	1161	−6	2[1]
		B	1402	1397	1385	−2	
		C	1330	1313	1307	−3	
Sensata (Texas Instruments)	4GS-1	A	1165	1164	1162	0	5
		B	867	877	873	1	
		C	935	941	931	−1	
Siemens	QPA2000	A	1223	1236	1251	4	±2
		B	1194	1209	1223	4	
		C	1285	1300	1311	3	
Telaire (GE Sensing)	Ventostat®8001	A	1230	1229	1229	0	NA
		B	1265	1268	1270	1	
		C	1184	1180	1177	−1	
Telaire (GE Sensing)	Ventostat®8002	A	1239	1218	1185	−7	NA
		B	1121	1151	1164	6	
		C	1205	1198	1199	−1	
Vaisala	GMW21	A	1096	1085	1079	−2	3[1]
		B	1202	1179	1153	−6	
		C	1230	1212	1194	−5	
Veris Industries	CWE SC	A	1265	1270	1264	0	NA
		B	1135	1134	1139	1	
		C	1190	1182	1183	−1	
Vulcain	90DM4SM-C-2000	A	1140	1153	1164	3	NA
		B	1274	1268	1266	−1	
		C	1121	1128	1136	2	

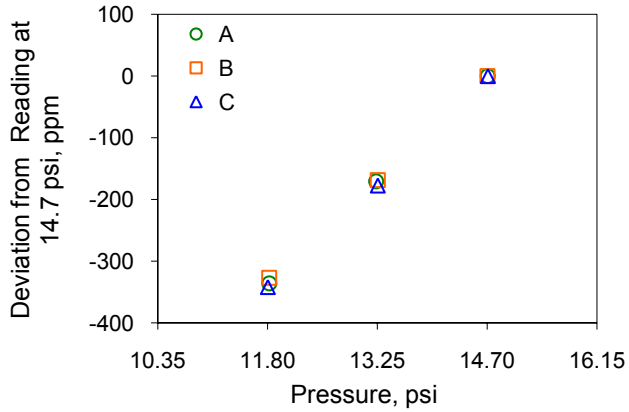
[1] *Value was calculated from the manufacturer's product literature.*

Pressure Sensitivity

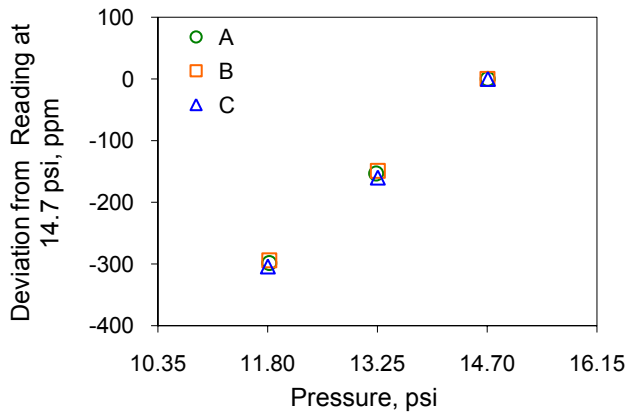
From the manufacturer data, as summarized in Table 1, eight of the fifteen CO_2 transmitter models state the dependency of pressure on the transmitter output. The remaining seven transmitter models do not specify any pressure dependency.

The effect of pressure on CO_2 transmitters was evaluated by varying the pressure in the test chamber while maintaining the chamber CO_2 concentration at 1100 ppm, an absolute humidity of 0.0069 lbm_v/lbm_a (kg_v/kg_a), and a temperature of 73 °F (22.8 °C). Sea-level pressure (14.7 psia) was used as the reference pressure. Transmitter readings were taken at pressures of 14.7 psia (101.35 kPa), 13.25 psia (91.35 kPa) and 11.80 psia (81.35 kPa). The deviation in transmitter readings was calculated from the difference of the transmitter readings at pressures of 13.25 psia (91.35 kPa) and 11.80 psia (81.35 kPa) and the transmitter reading at 14.7 psia (101.35 kPa). The results are shown in Figure 15.

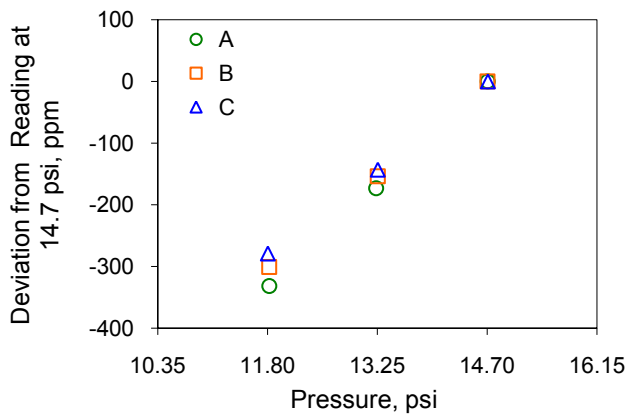
The pressure sensitivity of each CO_2 transmitter was calculated using a linear regression of the test results. The slope of the regression line represents the sensitivity of the transmitter in terms of deviation in percent reading per unit change in pressure. The sensitivity results are summarized in Table 11. All transmitters tested show sensitivity to pressure. This is to be expected since the molecular density of CO_2 is directly proportional to gas pressure.



15a. AirTest Technologies, Model TR9290

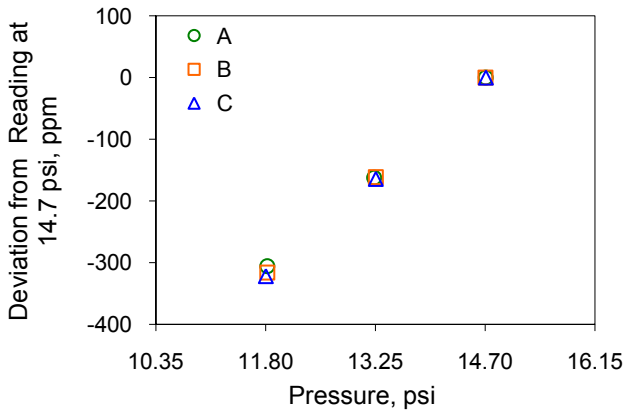


15b. AirTest Technologies, Model EE80-2CT3

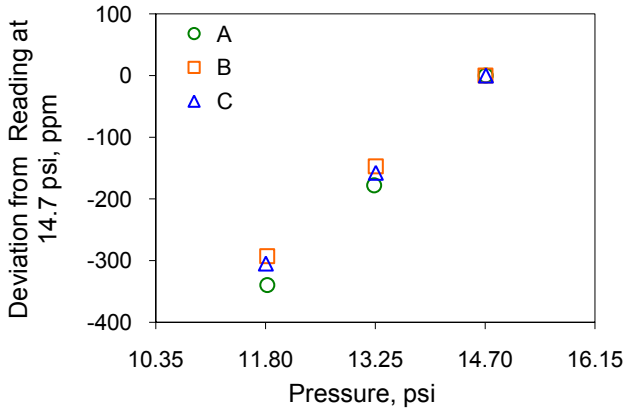


15c. Automation Components Inc, Model ACI/CO2-VDC-R

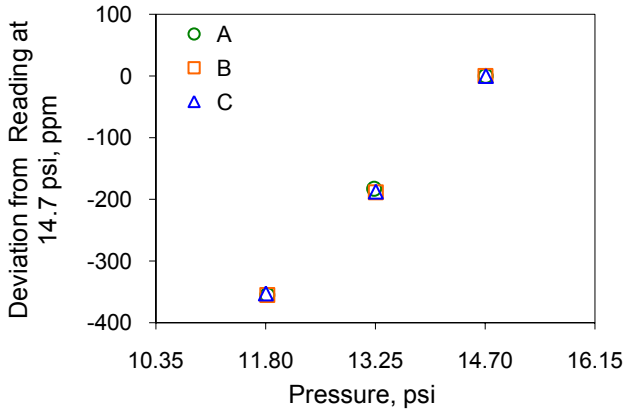
Figure 15. NBCIP measured pressure sensitivity of CO_2 transmitters.



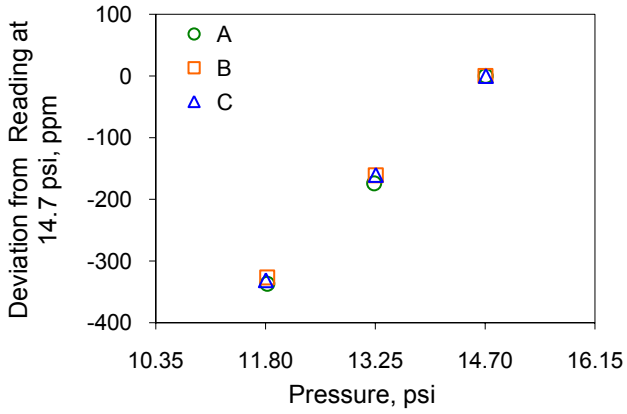
15d. Digital Control Systems Inc, Model AirSense™ M307



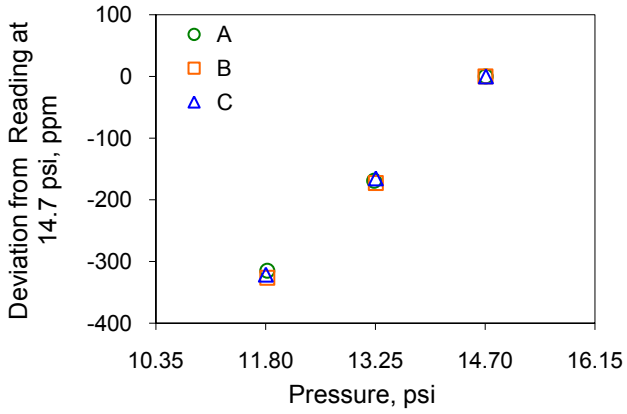
15e. Greystone Energy Systems Inc, Model CDD1A2000



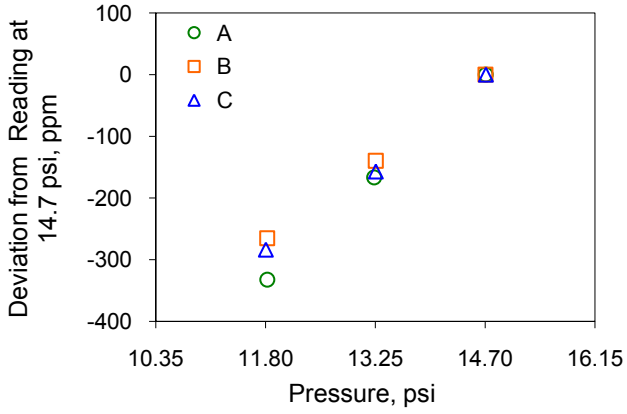
15f. Honeywell, Model C7232A1016



15g. Intec Controls Inc, Model I-310E

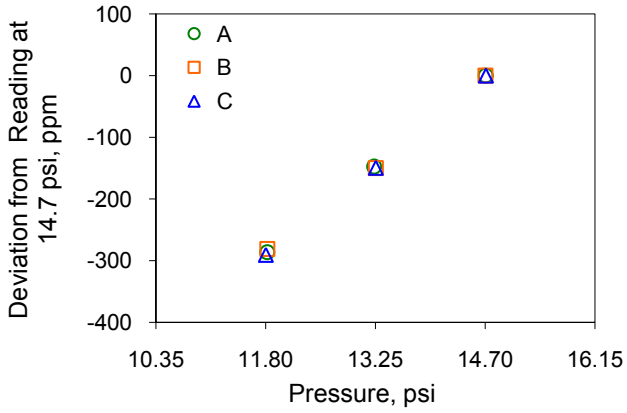


15h. Johnson Controls, Model CD-WA0-00-0

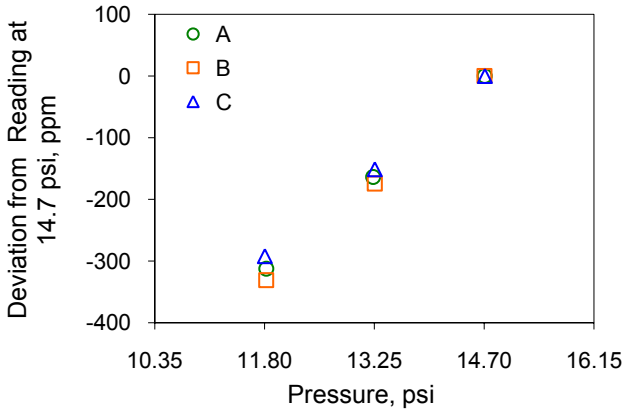


15i. Sensata (Texas Instruments), Model 4GS-1

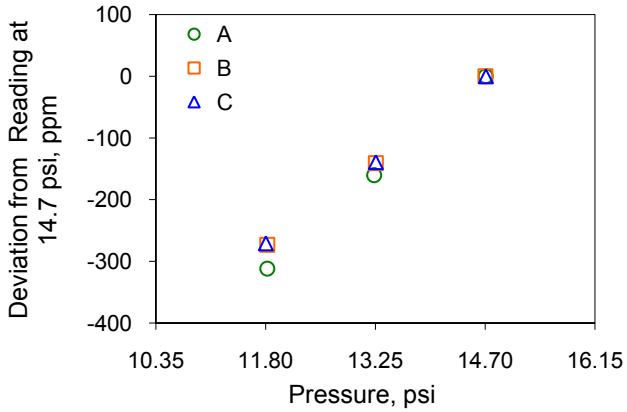
Figure 15. (continued) NBCIP measured pressure sensitivity of CO_2 transmitters.



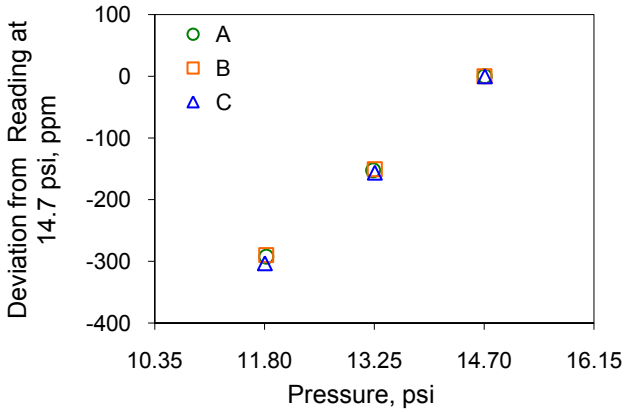
15j. Siemens, Model QPA2000



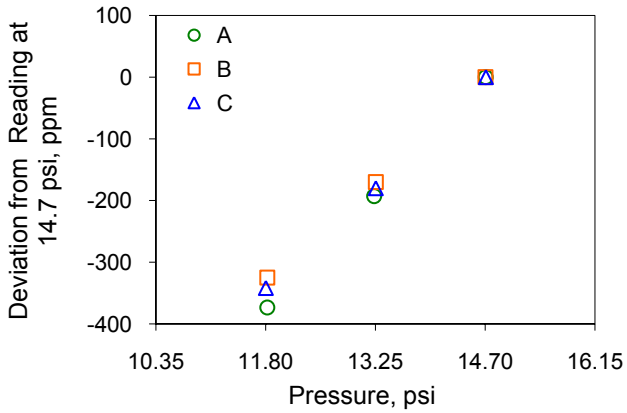
15k. Telaire (GE Sensing), Model Ventostat®8001



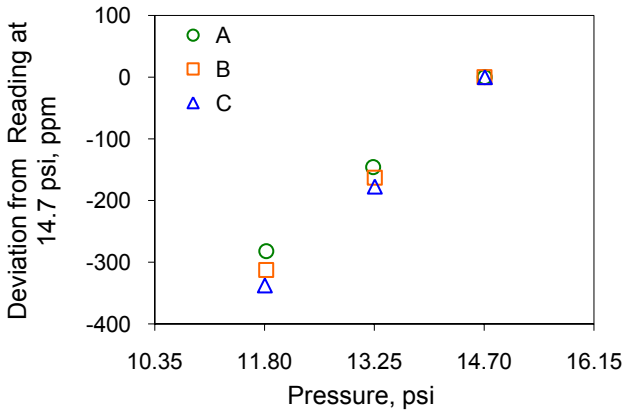
15l. Telaire (GE Sensing), Model Ventostat®8102



15m. Vaisala, Model GMW21



15n. Veris Industries, Model CWE SC



15o. Vulcain, Model 90DM4SM-C-2000

Figure 15. (continued) NBCIP measured pressure sensitivity of CO_2 transmitters.

Table 11. NBCIP test results for pressure sensitivity of CO_2 transmitters.

Manufacturer	Model Number	Transmitter	Reading at 14.70 psia (101.35 kPa), ppm	Reading at 13.25 psia (91.36 kPa), ppm	Reading at 11.80 psia (81.36 kPa), ppm	Pressure Sensitivity, % Reading / psi (6.89 kPA) Calculated	Pressure Sensitivity, % Reading / psi (6.89 kPA) Manufacturer Specified
AirTest Technologies	TR9290	A	1186	1018	853	9.8	NA
		B	1149	980	980	9.9	
		C	1184	1007	842	9.9	
AirTest Technologies	EE80-2CT3	A	1275	1121	976	8.1	NA
		B	1246	1097	1097	8.2	
		C	1277	1117	972	8.2	
Automation Components Inc.	ACI/CO2-VDC-R	A	1275	1102	944	9.0	6.7[1]
		B	1171	1017	1017	8.9	
		C	1114	971	835	8.6	
Digital Control Systems Inc.	AirSense™ M307	A	1330	1167	1024	8.0	NA
		B	1343	1182	1182	8.2	
		C	1438	1274	1116	7.7	
Greystone Energy Systems Inc.	CDD1A2000	A	1315	1137	975	9.0	6.7[1]
		B	1210	1063	1063	8.4	
		C	1214	1056	909	8.6	
Honeywell	C7232A1016	A	1240	1057	884	9.9	9.6[1]
		B	1204	1016	1016	10.2	
		C	1237	1050	885	9.8	
Intec Controls Inc.	I-310E	A	1539	1365	1203	7.6	7.2[1]
		B	1457	1296	1296	7.8	
		C	1485	1325	1154	7.7	
Johnson Controls	CD-WA0-00-0	A	1185	1016	870	9.2	10.2[1]
		B	1388	1216	1216	8.2	
		C	1313	1148	992	8.4	
Sensata (Texas Instruments)	4GS-1	A	1161	995	829	9.9	9.8[1]
		B	862	722	722	10.7	
		C	914	757	630	10.7	
Siemens	QPA2000	A	1238	1090	952	8.0	NA
		B	1206	1056	1056	8.1	
		C	1293	1143	1002	7.7	
Telaire (GE Sensing)	Ventostat®8001	A	1233	1070	921	8.8	6.7[1]
		B	1267	1093	1093	9.1	
		C	1180	1029	888	8.5	
Telaire (GE Sensing)	Ventostat®8002	A	1212	1051	900	8.9	6.7[1]
		B	1143	1002	1002	8.3	
		C	1202	1063	931	7.8	
Vaisala	GMW21	A	1087	935	795	9.3	NA
		B	1175	1025	1025	8.6	
		C	1219	1062	915	8.6	
Veris Industries	CWE SC	A	1260	1067	886	10.3	NA
		B	1132	962	962	10.0	
		C	1187	1007	845	9.9	
Vulcain	90DM4SM-C-2000	A	1150	1004	867	8.5	NA
		B	1263	1100	1100	8.6	
		C	1143	965	805	10.2	

[1] *Value was calculated from the manufacturer's product literature.*

Conclusions

The result from the tests conducted under accurate and repeatable conditions showed a wide variation in transmitter performance among the fifteen NDIR CO_2 transmitter models. In some cases, significant variations in transmitter performance exist between transmitters of the same model while in other cases, all transmitters of the same model showed almost identical behavior.

None of the transmitter models meet their manufacturer specified accuracy statement for all three transmitters of a given model over the full range of test conditions. For some models, none of the transmitters meet the accuracy specifications over the range. Table 12 summarizes the transmitter models and the number of transmitters of the given model that meet the manufacturer's accuracy statement for the model. It is important to note that there is a wide variation in accuracy statements among the manufacturers, and the results presented in the table are not an indication of the performance between the various transmitter models.

Given the test results and that the transmitters were tested under "as received" conditions, it appears that transmitter calibration should be performed before putting a transmitter into service.

However, for transmitters with an automatic baseline adjustment algorithm, it is impossible to predict the transmitter's performance over a prolonged time period during which the transmitter baseline might make multiple adjustments. In fact, the product data for several transmitter models that incorporate an automatic baseline adjustment algorithm claim that the transmitters do not require calibration. Given the transmitter is "self adjusting" using an arbitrary baseline reading of 400 ppm, it is unclear how the transmitter manufacturer can claim an absolute accuracy for their transmitter. However, some of the models that utilize automatic baseline adjustment algorithm do appear to be "accurate" if one accounts for the bias created by the baseline adjustment. For example, all three AirTest Technologies TR9290 transmitters (Figure 9a) would perform as specified if the transmitter readings were adjusted downward by approximately 50 ppm. The same is true for several other non self-adjusting transmitters that show a relatively constant value of deviation as the CO_2 concentration is increased. For transmitters that show increasingly larger values of deviation as the CO_2 concentration increases (see Figure 9g), a simple bias adjustment would not make the transmitter reading accurate over the full range of CO_2 concentrations.

Table 12. CO_2 Transmitter accuracy summary.

Manufacturer	Model Number	All 3 transmitters meet the manufacturer's accuracy statement	2 transmitters meet the manufacturer's accuracy statement	1 transmitter meets the manufacturer's accuracy statement	None of the transmitters meet the manufacturer's accuracy statement
AirTest Technologies	TR9290			■	
AirTest Technologies	EE80-2CT3				■
Automation Components Inc.	ACI/CO2-VDC-R		■		
Digital Control Systems Inc.	AirSense™ M307				■
Greystone Energy Systems Inc.	CDD1A2000				■
Honeywell	C7232A1016				■
Intec Controls Inc.	I-310E				■
Johnson Controls	CD-WA0-00-0				■
Sensata (Texas Instruments)	4GS-1				■
Siemens	QPA2000				■
Telaire (GE Sensing)	Ventostat®8001			■	
Telaire (GE Sensing)	Ventostat®8002			■	
Vaisala	GMW21				■
Veris Industries	CWE SC			■	
Vulcain	90DM4SM-C-2000		■		

Given the sensitivity of a NDIR CO_2 transmitter reading to pressure, it is of interest to estimate the expected change in a transmitter's reading due to the natural variation in barometric pressure for a given location. Using TMY2 weather data, the maximum change in barometric pressure was determined for nine US cities. From the CO_2 transmitter sensitivity test results, the average pressure sensitivity is 8.9% reading/psi (6.89 kPa). Applying this sensitivity to the barometric pressure variation for each of the nine cities, the expected variation in CO_2 transmitter readings were calculated. Table 13 summarizes the results. For the nine cites considered, Boston, Chicago and New York have the largest variation in barometric pressure. For these locations, the expected variation in a CO_2 transmitter reading is 84 ppm for actual CO_2 concentration at 1100 ppm. The significance of these results is important when considering transmitter calibration. Even for a "perfectly" calibrated transmitter, the reading could be in error by several ppm depending on the barometric pressure at the time the transmitter was calibrated compared to the barometric pressure at other times of the year.

Based on the test results presented in this report, there is no clear indication that one particular transmitter technology is superior to another when the transmitters are "new". As described in the Introduction, various transmitter configurations are employed to overcome the "ageing" of the lamp or other degradations effects that may occur over time. These issues will be addressed at the conclusion of the long-term performance testing which is described in the next section.

Table 13. Expected Variation in CO_2 Transmitter Output due to Variation in Local Barometric Pressure (at 1100 ppm CO_2 Concentration).

Location	Variation in Barometric Pressure, psi (kPa)	Variation in CO_2 Reading, ppm
Atlanta	0.508 (3.502)	50
Boston	0.860 (5.930)	84
Chicago	0.855 (5.895)	84
Denver	0.590 (4.068)	58
Los Angeles	0.566 (3.902)	55
Miami	0.377 (2.599)	37
New York	0.855 (5.895)	84
Sacramento	0.435 (2.999)	43
San Francisco	0.493 (3.399)	48

Next Steps

NBCIP is currently evaluating the long-term performance of the CO_2 transmitters discussed in this report. All transmitters are being exposed to the same environmental conditions in the laboratory space of the H.M. Black Engineering Building at Iowa State University. Every four months, transmitters will be placed in the test chamber and subjected to the same set of test conditions described in this report. Data collected will be used to evaluate the transmitter performance over a one-year time period. Results of this testing will be reported to the public as a supplement to this report.

Terms and Definitions

Accuracy:

Accuracy is the deviation of the CO_2 concentration measured by a CO_2 transmitter from the actual, or known, CO_2 concentration.

Actual CO_2 Concentration:

The actual CO_2 concentration of the dry gas mixture is the reading from Environics gas mixing system. The actual CO_2 concentration of the moist gas mixture was calculated based on an ideal gas model of a mixture of water vapor and the dry gas mixture. Water vapor content will be calculated based on ideal gas psychrometric relations and measured values of pressure, temperature and relative humidity.

CO_2 Transmitter:

A device that consists of a sensor as well as a transducer that converts the sensor reading into an output signal.

Deviation:

Deviation is the difference between the measured and actual CO_2 concentration at a given test condition, and is defined by the following equation:

Deviation = measured CO_2 concentration – actual CO_2 concentration

NBCIP calculated the deviation for each CO_2 transmitter at each test condition. Mean deviation for a given transmitter at a given condition was calculated by averaging the deviation of the first forward measurement and the deviation of the reverse measurement.

Humidity Sensitivity:

Humidity sensitivity is the deviation of the carbon dioxide concentration measured by a CO_2 transmitter from the actual, or known, carbon dioxide concentration due to a variation in relative humidity.

Hysteresis:

Hysteresis is the error in measurement when the same CO_2 concentration is approached from a lower and then higher CO_2 concentration (at a fixed temperature, pressure, and humidity).

Linearity:

Linearity is the extent to which the CO_2 transmitter input and output can be approximated by a linear function.

Pressure Sensitivity:

Pressure sensitivity is the deviation of the carbon dioxide concentration measured by a CO_2 transmitter from the actual, or known, carbon dioxide concentration due to a pressure variation.

Repeatability:

Repeatability is the degree to which a CO_2 transmitter produces the same measurement when subjected repeatedly to the same conditions as these conditions are approached from the same direction.

Temperature Sensitivity:

Temperature sensitivity is the deviation of the carbon dioxide concentration measured by a CO_2 transmitter from the actual, or known, carbon dioxide concentration due to a temperature variation.

References

ASHRAE, 2005 Handbook – *Fundamentals, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc. Atlanta, GA*

Dougan, D.S., and L. Damiano. 2004. CO_2-based demand control ventilation: do risk outweigh potential rewards?. *ASHRAE* Journal Vol. 46, No. 10: 47-53

Emmerich, S. J., and A. K. Persily. 2001. *State-of-the-art review of CO_2 demand controlled ventilation technology and application, Report NISTIR 6729, National Institute of Science and Technology (NIST), USA.*

Environics®, Series 4000 Multi Component Gas Mixing System product data, http://www.environics.com/4000.html

Federal Energy Management Program (FEMP), Energy Efficiency and Renewable Energy, U.S. Department of Energy, 2004, http://www1.eere.energy.gov/femp/pdfs/fta_co2.pdf

Roth, K.W., D. Westphalen, M.Y. Pheng, P. Llana, and L. Quartararo. 2005. Energy impact of commercial building controls and performance diagnostics: Market characterization, energy impact of building faults and energy saving potential. http://www.tiaxllc.com/aboutus/pdfs/energy_imp_comm_bldg_cntrls_perf_diag_110105.pdf

Solid State Pressure Transducer, http://www.omega.com/ppt/pptsc.asp?ref=PX209_PX219&Nav=preb03

Vaisala HUMICAP® Humidity and Temperature Transmitter Series HMT330, http://www.vaisala.com/instruments/products/humidity/fixed/hmt330

Vaisala, GMP343 Carbon Dioxide Probe for Demanding Measurements, http://www.vaisala.com/businessareas/instruments/products/carbondioxide/gmp343/product%20documentation/brochures/gmp343%20brochure%20in%20english.pdf?SectionUri=%2fbusinessareas%2finstruments%2fproducts%2fcarbondioxide%2fgmp343%2fproduct%2520documentation&TabDoc=open

Appendix A: E-mail sent to CO_2 Transmitter Suppliers

Dear <CO_2 Sensor Supplier>:

Congratulations, <one or two> of your CO_2 sensor products has been selected for independent testing as part of National Building Controls Information Program (NBCIP). NBCIP was established by the Iowa Energy Center with support from the U.S. Environmental Protection Agency to facilitate the adoption of energy efficient building control products and strategies through testing, demonstration, education and dissemination of product information. The NBCIP provides unbiased, accurate, reliable, manufacturer-specific information on building control systems to guide and improve the selection, installation, operation and maintenance of control products and strategies for building applications. With the support of government agencies, electric utilities and public benefit organizations, the NBCIP addresses a critical energy management issue that impacts every state in the nation. To ensure objectivity, NBCIP does not accept funding from manufacturers. Additional information about the NBCIP program is available at http://www.buildingcontrols.org.

CO_2 sensor testing will be performed under contract with Iowa State University. For testing purposes, we will purchase two <specific model> sensors from you or your supplier. Ordering information has been obtained from your company web site and we will proceed to place our order from the information found there unless you have a specific supplier from which you wish us to purchase the sensors. Our intent is to purchase "off the shelf" sensors.

We also request that you identify a technical representative who can respond to questions that might arise and who can review technical specifications on behalf of your product.

Thank you for your assistance in this request. We look forward to hearing from you at your earliest convenience.

Sincerely,

Gregory Maxwell

Principal Investigator, NBCIP CO_2 Sensor project

Appendix B: Technical Specification of Test Apparatus and Test Chamber Instrumentation

Table 14. Technical specifications of the Environics Series 4000 gas mixing system.

Accuracy	
Concentration	±1.0% Setpoint
Flow	±1.0% Setpoint
Repeatability	±0.05% Setpoint
Warm up time	30 minutes
Operating pressure at inlet	
Recommended	25 psig (1.68 Bar)
Minimum	10 psig (0.67 Bar)
Maximum	75 psig (5.04 Bar)
Operating temperature	32°F to 104°F (0°C to 40°C)
Performance temperature	59°F to 95°F (15°C to 35°C)
Electronics	12 Bit A/D and D/A conversion, RS232 serial interface
Full scale flow of mass flow controller 1 (N_2)	3 SLPM
Full scale flow of mass flow controller 2 (CO_2)	0.01 SLPM

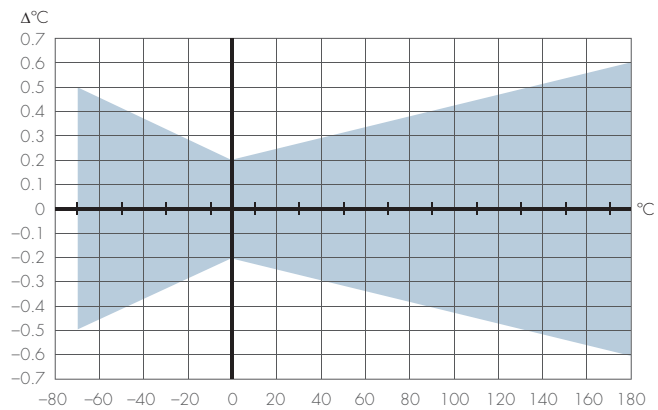
Table 15. Technical specifications of the test chamber absolute pressure transmitter.

Description	Value
Measurement range	0 to 15 psia
Accuracy	0.25% FS
Operating temperature	−65 to 250°F (−54 to 121°C)
Response time	2 ms

Table 16. Technical specifications of the test chamber humidity and temperature transmitter.

Description	Value
Relative humidity	
Measurement range	0 to 100%
Accuracy	
at 59 to 77°F (15 to 25°C)	±1% RH (0 to 90%), ±1.7% RH (90 to 100%)
at −4 to 104°F (−20 to 40°C)	± (1.0 + 0.008 x reading) %RH
Temperature	
Measurement range	−94 to 356°F (−70 to 180°C)
Accuracy at 68°F (20°C)	±0.36°F (±0.2°C)

Accuracy over temperature range



Environics®

nqa. ISO 9001 Registered ANAB ACCREDITED

Series 4000

System S/N 3866

ENVIRONICS FLOW CONTROLLER CALIBRATION SHEET

MFC#: 1 Size: 3000 SCCM

SERIAL NUMBER 3460300001

This flow controller was calibrated using a Sierra Cal Bench ™, a NIST traceable Primary Flow Standard Calibration System. This calibration was performed with Nitrogen at a standard reference temperature and pressure of 32° and 29.92 in.HG. This is not performance data. This data is used by the system operating modes to improve the flow accuracy.

	Set Flow	True Flow
5 %	150.0 CCM	144.961 CCM
10 %	300.0 CCM	300.898 CCM
20 %	600.0 CCM	611.227 CCM
30 %	900.0 CCM	916.871 CCM
40 %	1200.0 CCM	1222.087 CCM
50 %	1500.0 CCM	1524.450 CCM
60 %	1800.0 CCM	1826.889 CCM
70 %	2100.0 CCM	2129.436 CCM
80 %	2400.0 CCM	2436.573 CCM
90 %	2700.0 CCM	2745.581 CCM
100 %	3000.0 CCM	3063.990 CCM

Verified by: _____ Date: 8-17-07

Computerized Gas Mixing / Dilution / Calibration Systems

Environics Inc. • 69 Industrial Park Road East • Tolland, CT 06084 • (860) 872-1111 • Fax (860) 870-9333

World Wide Web: http://www.environics.com E-mail: info@environics.com

Figure 16. Certificate of Calibration

Environics®

nqa. ISO 9001 Registered ANAB ACCREDITED

Series 4000

System S/N 3866

ENVIRONICS FLOW CONTROLLER CALIBRATION SHEET

MFC#: 2 Size: 10 SCCM

SERIAL NUMBER 3460400001

This flow controller was calibrated using a Sierra Cal Bench ™, a NIST traceable Primary Flow Standard Calibration System. This calibration was performed with Carbon Dioxide at a standard reference temperature and pressure of 32° and 29.92 in.HG. This is not performance data. This data is used by the system operating modes to improve the flow accuracy.

	Set Flow	True Flow
5 %	0.5 CCM	0.470 CCM
10 %	1.0 CCM	0.956 CCM
20 %	2.0 CCM	1.920 CCM
30 %	3.0 CCM	2.943 CCM
40 %	4.0 CCM	3.988 CCM
50 %	5.0 CCM	5.029 CCM
60 %	6.0 CCM	6.065 CCM
70 %	7.0 CCM	7.079 CCM
80 %	8.0 CCM	8.139 CCM
90 %	9.0 CCM	9.206 CCM
100 %	10.0 CCM	10.303 CCM

Verified by: _____ Date: 8-17-07

Computerized Gas Mixing / Dilution / Calibration Systems

Environics Inc. • 69 Industrial Park Road East • Tolland, CT 06084 • (860) 872-1111 • Fax (860) 870-9333

World Wide Web: http://www.environics.com E-mail: info@environics.com

Figure 16. (Continued)

Appendix C: Compensating CO_2 Concentration for Moisture Content

For a dry-gas mixture of nitrogen and carbon dioxide, the concentration of $CO_{2,d}$ (The subscript, *d*, is used to emphasize the dry-gas mixture) is achieved by accurately controlling the mass flow rate of each gas during the mixing process. This process is controlled by the Environics Gas Mixing system. The concentration of the $CO_{2,d}$ in units of parts per million (*ppm*) is the volume fraction of the $CO_{2,d}$ expressed as volume units of $CO_{2,d}$ per 10^6 volume units of mixture. When water vapor is subsequently added to the mixture, (as a result of bubbling the dry gas through a water column), the total number of moles in the mixture increases and the concentration of $CO_{2,d}$ is reduced. Thus in order to achieve a particular value of CO_2 concentration in the moist gas mixture, a higher value of $CO_{2,d}$ concentration must be produced by the Environics Gas Mixing system.

Determination of the CO_2 concentration in the new mixture requires knowledge of the concentration of water vapor in the moist-gas mixture. The concentration of water vapor present in a mixture of gases can be calculated based on psychrometric relations for ideal gas mixtures and values of three independent thermodynamic properties such as pressure, temperature and relative humidity. The concentration of water vapor is directly related to the partial pressure of water vapor (P_w) in the mixture as given by Equation (C-1).

The partial pressure of the water vapor is related to the relative humidity and saturation pressure (P_{ws}) of water

$$ppm_w = \frac{P_w(10^6)}{P} \qquad \text{(C-1)}$$

through the definition of relative humidity (ø) as given by Equation (C-2).

$$ø(\%) = \frac{P_w}{P_{ws}} * 100 \qquad \text{(C-2)}$$

Saturation pressure of the water vapor (P_{ws}) is only a function of temperature and is computed using the formula by Hyland and Wexler as given by Equation (C-3).

$$\ln P_{ws} = \frac{C_8}{T} + C_9 + C_{10}T + C_{11}T^2 + C_{12}T^3 + C_{13}\ln T \qquad \text{(C-3)}$$

where

C_8 = −1.044 039 7 E+04

C_9 = −1.129 465 0 E+01

C_{10} = −2.702 235 5 E−02

C_{11} = 1.289 036 0 E−05

C_{12} = −2.478 068 1 E−09

C_{13} = 6.545 967 3 E+00

T = gas temperature (°R)

P_{ws} = saturation pressure (psia)

The mole fraction of water molecules (y_w) in a gas mixture is computed from the ratio of the partial pressure of the water vapor (P_w) to the mixture pressure (P) as given in Equation (C-4).

$$y_w = \frac{P_w}{P} = \frac{n_w}{n} \qquad \text{(C-4)}$$

In Equation (C-4), n_w is the number of moles of water vapor and n is the total number of moles in the mixture.

Multiplying the number of moles by Avogadro's number (N_A) gives the number of molecules (N) in a given moles of gas, hence:

$$\frac{n_w}{n} = \frac{n_w(N_A)}{n(N_A)} = \frac{N_w}{N} \qquad \text{(C-5)}$$

In Equation (C-5), N_w is the number of H_2O molecules and N is the total number of molecules in the mixture.

Applying Avogadro's hypothesis, the concentration of H_2O molecules in the mixture (ppm_w) by volume yields:

$$ppm_w = \frac{N_w(10^6)}{N} = \frac{P_w(10^6)}{P} \qquad \text{(C-6)}$$

Then the required CO_2 concentration of the dry gas ($ppm_{CO_2,d}$) from the gas mixing system to get the desired CO_2 concentration after adding water vapor (ppm_{CO_2}) can be calculated as:

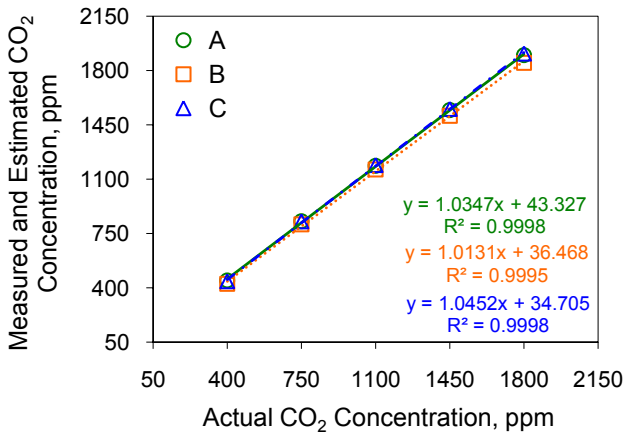
$$ppm_{CO_2,d} = ppm_{CO_2}\left(1 + \frac{ppm_w}{10^6 - ppm_w}\right) \quad \text{(C-7)}$$

Table 17 shows the required $CO_{2,d}$ concentration of the dry gas mixture from the gas mixing system to obtain the desired CO_2 concentration of the moist gas mixture in the test chamber for various CO_2 concentrations and relative humidities at 73°F temperature and 14.7 psia pressure.

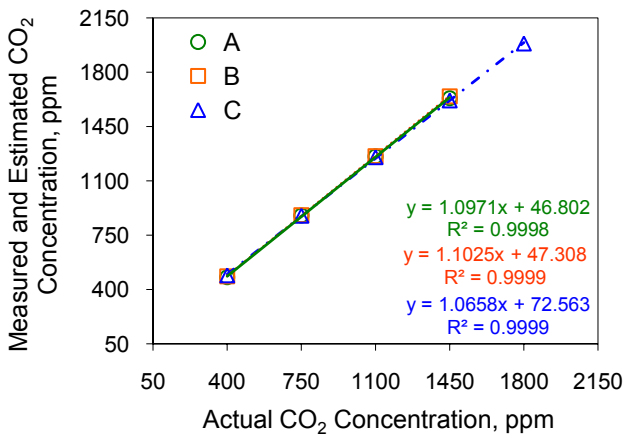
Table 17. CO_2 concentration correction values.

Desired CO_2 Concentration of the moist gas mixture (ppm_{CO_2}), ppm	Relative Humidity of the gas mixture (ø),%	Required CO_2 Concentration of the dry gas mixture from the Gas Mixing System(ppm_{CO_2}), ppm
400	40	404.4
750	40	758.3
1100	40	1112.1
1450	40	1466.0
1800	40	1819.9
1100	20	1106.0
1100	60	1118.3

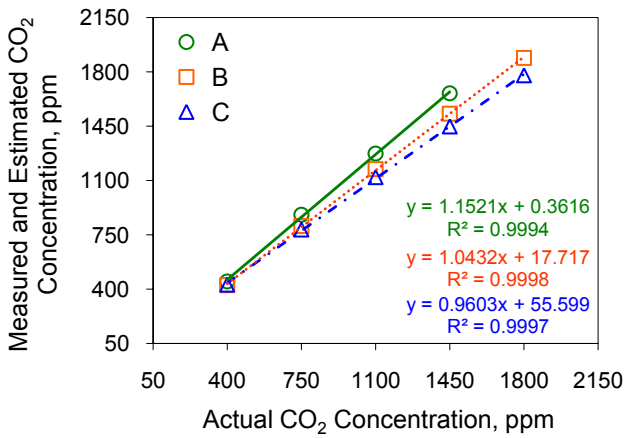
Appendix D: NBCIP measured linearity of CO_2 transmitters



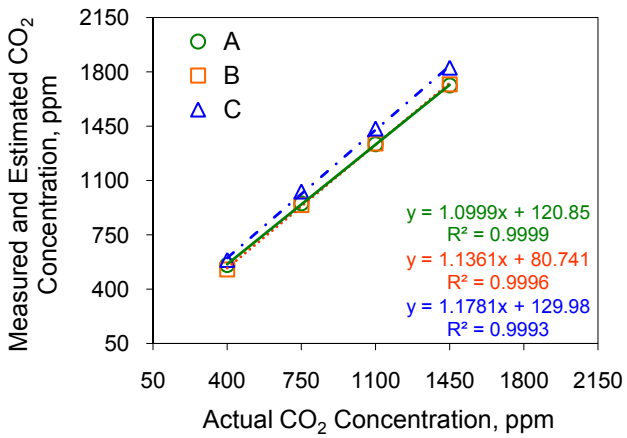
17a. AirTest Technologies, Model TR9290



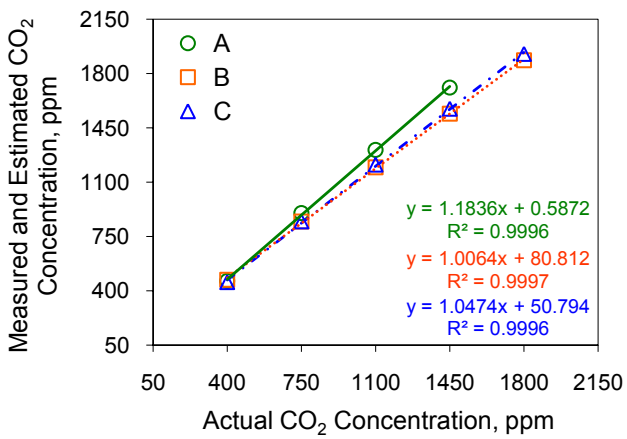
17b. AirTest Technologies, Model EE80-2CT3



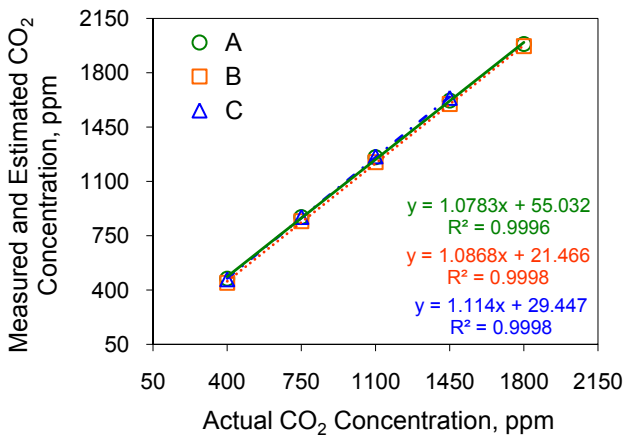
17c. Automation Components Inc, Model ACI/CO2-VDC-R



17d. Digital Control Systems Inc, Model AirSense™ M307

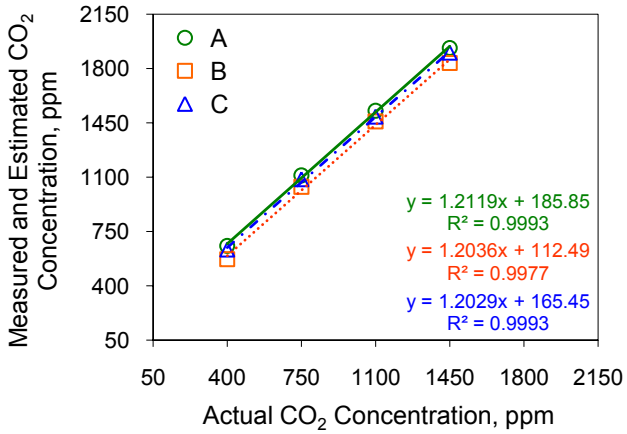


17e. Greystone Energy Systems Inc, Model CDD1A2000

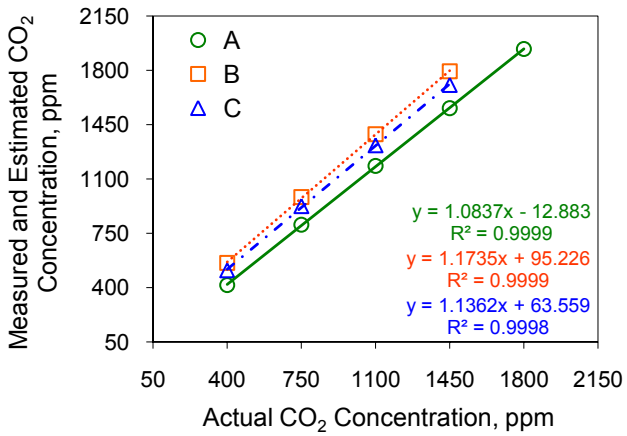


17f. Honeywell, Model C7232A1016

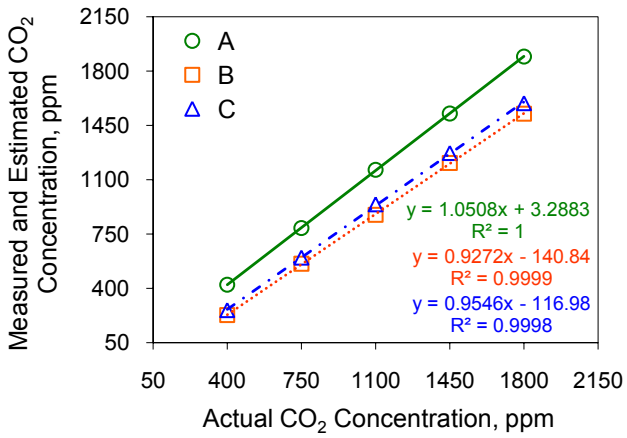
Figure 17. NBCIP measured linearity of carbon dioxide transmitters.



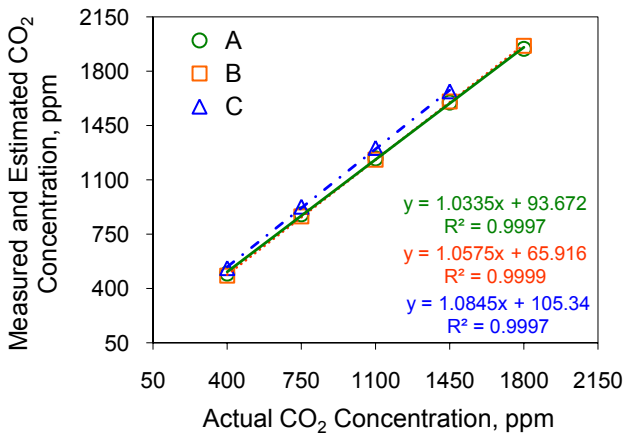
17g. Intec Controls Inc, Model I-310E



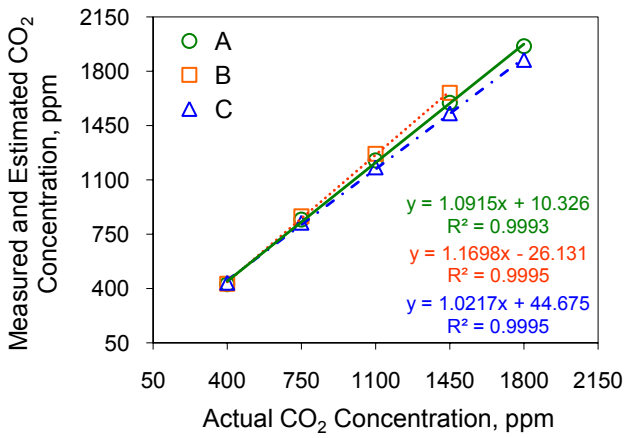
17h. Johnson Controls, Model CD-WA0-00-0



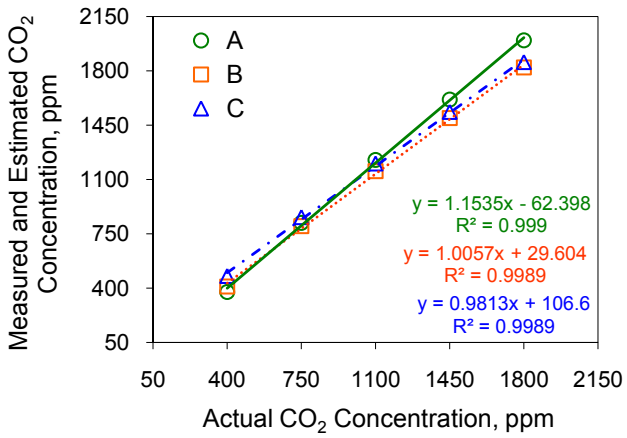
17i. Sensata (Texas Instruments), Model 4GS-1



17j. Siemens, Model QPA2000

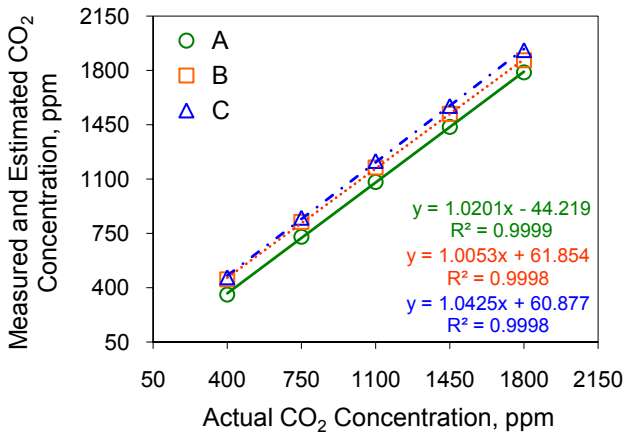


17k. Telaire (GE Sensing), Model Ventostat®8001

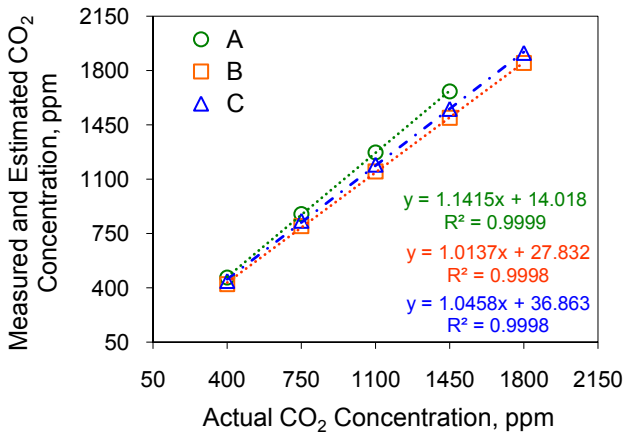


17l. Telaire (GE Sensing), Model Ventostat®8102

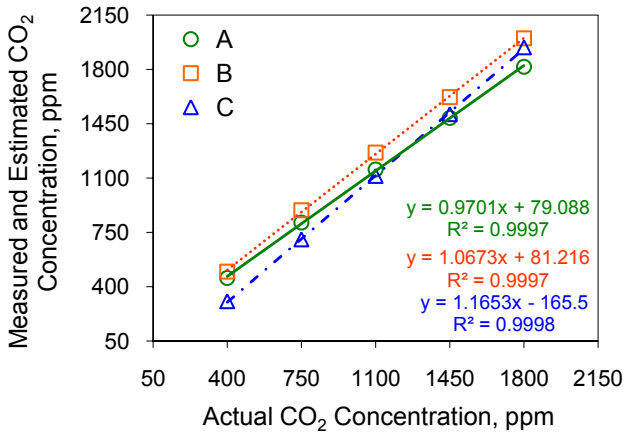
Figure 17. continued NBCIP measured linearity of carbon dioxide transmitters.



17m. Vaisala, Model GMW21



17n. Veris Industries, Model CWE SC



17o. Vulcain, Model 90DM4SM-C-2000

Figure 17. continued NBCIP measured linearity of carbon dioxide transmitters.

Product Testing Report Wall-Mounted CO_2 Humidity Transmitters

Principal Investigators: Som Shrestha, Iowa State University; Gregory Maxwell, Iowa State University

NBCIP Project Manager: Curtis J. Klaassen

Report Authors: Som Shrestha and Gregory Maxwell

Project Technical Director: Curtis J. Klaassen

The following persons provided technical review of this report: James Braun, Purdue University; Steven J. Emmerich, National Institute of Standards and Technology; William Fisk, Lawrence Berkeley National Laboratory; Steven Taylor, Taylor Engineering, LLC.

The following persons provided technical review of the method of test: Steven J. Emmerich, National Institute of Standards and Technology; William Fisk, Lawrence Berkeley National Laboratory; James Braun, Purdue University.

Reviewers are listed to acknowledge their contributions to the final publication. Their approval or endorsement of this report is not necessarily implied.

COPYRIGHT NOTICE.

Copyright © 2008 Iowa State University, the Iowa Energy Center. All rights are reserved by Iowa State University, and no portion of this publication or the information contained herein may be reproduced, disseminated, published, transferred, or excerpted in any way in other publications, databases, web sites or any other medium without express written permission of Iowa State University's Iowa Energy Center. Permission is granted to an individual to print copies of all or part of this publication solely for their own personal use and not for any other use. Any other use without written permission is a violation of United States copyright laws. Permission is not granted for use of the data contained in this publication for product publicity purposes. The NBCIP and Iowa Energy Center logos may not be used in any advertising or publicity, or otherwise to indicate NBCIP's or the Iowa Energy Center's sponsorship of or affiliation with any product or service.

The products described herein have not been tested for safety. The Iowa Energy Center and Iowa State University make no representations whatsoever with regard to the safety of products, in whatever form or combination used, and the results of testing set forth for your information cannot be regarded as a representation that the product is or is not safe to use in any specific situation, or that the particular product you purchase will conform to the results found in this report.

The National Building Controls Information Program

The National Building Controls Information Program (NBCIP) was established by the Iowa Energy Center in 2001 with support from the U.S. Environmental Protection Agency to facilitate the adoption of energy efficient building control products and strategies through testing, demonstration, education and dissemination of product information. The Iowa Energy Center has launched this national initiative based on our investment in the Energy Resource Station, a unique facility that serves as NBCIP's testing laboratory, and the expertise our researchers have acquired in building controls.

NBCIP recognizes that improving the operation of control systems is a major energy saving opportunity. NBCIP research is aimed at understanding the cause of problems with building controls, evaluating the performance of control systems and strategies, and developing best-practice recommendations for implementing energy-efficient control strategies.

NBCIP provides unbiased, accurate, reliable, manufacturer-specific information on building control systems to guide and improve the selection, installation, operation and maintenance of control products and strategies for building applications.

NBCIP establishes building control product performance in a consistent manner. The NBCIP label signifies that testing was performed using an established process that includes peer review of the method of test and the test results. To ensure objectivity, NBCIP does not accept funding from control product manufacturers.

Contacting NBCIP

National Building Controls Information Program
Iowa Energy Center, Energy Resource Station
DMACC, 2006 S. Ankeny Blvd.
Ankeny, IA 50021

Phone: (515) 965-7055

Fax: (515) 965-7056

E-mail: nbcip@energy.iastate.edu

Visit NBCIP online at: **www.buildingcontrols.org**