U.S. EPA BASE STUDY
STANDARD OPERATING PROCEDURE
FOR CONTINUOUS MONITORING
OF INDOOR AIR

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TABLE OF CONTENTS

LIST OF TABLES

ABBREVIATIONS AND ACRONYMS

BASE	Building Assessment Survey and Evaluation
CO	carbon monoxide
CO_2	carbon dioxide
dB	decibel
NIST	National Institute for Standards and Technology
ppm	parts per million
RH	relative humidity
SOP	standard operating procedure

1.0 OBJECTIVE

The procedure described is intended for monitoring continuously and simultaneously, at selected work sites, parameters that are most commonly associated with the quality of indoor environments: the concentrations of carbon dioxide (CO_2), carbon monoxide (CO), temperature, relative humidity (RH), illumination, and noise. The measurements are conducted over a period of three full work days.

The performance of the building mechanical systems in ventilating and conditioning the indoor environment, as well as the assessment of CO_2 and CO source intensities, can be evaluated by simultaneously measuring and comparing the outdoor and indoor CO_2 and CO concentrations, relative humidity levels, and temperature. Outdoor measurements conducted under the Building Assessment Survey and Evaluation (BASE) Protocol are described in a separate standard operating procedure (SOP) titled *Outdoor Air Monitoring*.

The specific indoor environmental parameters that are part of this SOP include CO_2, CO, temperature, relative humidity, illuminance, and sound level measurements.

- CO_2 concentrations can be used as an indication of the amount of outdoor air introduced into an occupied space.

- CO concentrations can be used as an indicator of contamination from combustion-related exhaust systems (furnaces, engines, garages, or loading docks).

- The objective of temperature measurements is to accurately measure and/or monitor the temperature and vertical temperature gradients within the space during normal work hours. The objective of RH monitoring is to determine the relative humidity in the indoor environment during normal work hours. Together these measurements are essential in defining thermal comfort in an indoor environment.

- Illuminance is a basic comfort parameter in indoor environments. The quality and level of lighting can have an impact on occupants' perception of their indoor environment.

- Sound level is also a critical constituent of the core comfort parameters of indoor environments.

2.0 GENERAL PROCEDURES

2.1 MEASURING CRITERIA AND REQUIREMENTS

2.1.1 Metrosonics aq-502 Indoor Environmental Monitor

Metrosonics aq-502 is a versatile data-logger capable of measuring, displaying, and recording data on up to thirteen channels. The standard unit comes with the following sensors: carbon dioxide, temperature, and relative humidity. In addition, this unit includes input channels for light, sound, air velocity, as well as five gas/voltage channels. The following parameters will be detected using the aq-502: carbon dioxide, temperature (four tier stratification), relative humidity, sound, illumination (light), and carbon monoxide.

2.1.2 Carbon Dioxide Sensors

The CO_2 sensor employed is part of the aq-502 Indoor Environmental Monitor manufactured by Metrosonics. The CO_2 sensor is built into the aq-502 and may not be removed. These active sensors employ non-dispersive infrared radiation (NDIR) adsorption to quantify the concentration of CO_2 present in a gas stream. The instrument output is a voltage that relates linearly to CO_2 concentration in the 0 to 5,000 parts per million (ppm) range. The precision (repeatability) of the instrument is, according to the manufacturer's specifications, 3% of full scale. Calibration records at EH&E show a repeatability for different instruments and at different times in the range of 0 to 40 ppm, based on measurements with gases of known concentrations. For comparison, the BASE Method Performance Requirement is ±50 ppm. The manufacturer's specified accuracy of the instrument is 3% of the reading or ±50 ppm, whichever is greater. Calibration records held at EH&E show average deviations of -13 to 28 ppm for the 0 to 1,000 ppm concentration range. These criteria are given here to facilitate a rational evaluation of the results of span checks and calibrations conducted under field conditions.

The operating temperature range for the CO_2 sensors is 0°C to 50°C, and the operating relative humidity range is 5% to 95% (non-condensing). The response time (time to

respond to 80% of perturbation) is approximately 20 seconds. A warm-up time of no less than 5 minutes is recommended.

2.1.3 Carbon Monoxide Sensors

The CO sensors employed are CiTiceL®, 7E/F aqueous electrolyte-based gas detectors (model gs-7701, manufactured by Metrosonics Inc.). The gas detected penetrates through a diffusion barrier and, upon equilibrating with the electrolyte solution, changes its conductivity in proportion to the equilibrium concentration of the gas species of interest (in this case CO). The instrument output is a voltage that relates linearly to the partial pressure (*i.e.*, concentration) of CO. The conductivity of the electrolyte is also affected by temperature and by the presence of some other gases in the atmosphere. Ethylene and hydrogen are the principal gases affecting CO concentration measurements. With regard to temperature effects, the cells are partly temperature compensated. According to the manufacturer (City Technology, Inc.), the mean square deviation from the true concentration in the temperature range of 10 to 40°C is less than 5%. EH&E's experience with CiTiceL® sensors is that, at low CO concentrations (< 5 ppm), a 5°C temperature variation can produce a variation in instrument response equivalent to 1 to 2 ppm of CO concentration. Repeated detector calibrations show mean square deviations (precision) ranging between 0.3 and 1.0 ppm (compared to the BASE method performance requirement of ±1 ppm). Similarly determined accuracies show deviations between 1.5 and 2.0 ppm (compared to the BASE method performance requirement of ±2 ppm).

Although the gs-7701 sensor meets the precision and accuracy criteria specified by the BASE protocol, these criteria conflict with the specified range of the instrument (0 ppm to 1000 ppm). The lower detection limit is about 5 ppm (accuracy plus three times the standard deviation). The manufacturer (City Technology, Inc.) specifies the sensor's baseline as readings between -1 and 3 ppm.

The nominal operating temperature range for the CO sensors is 0°C to 40°C, but the accuracy of the instrument is affected by temperature. According to the manufacturer's specifications, the sensor is calibrated for 20°C. In the 10°C to 30°C range the temperature coefficient of the measured CO concentration is approximately 0.40%/°C,

while the mean square deviation of readings registered by different sensors (*i.e.*, accuracy) is approximately 2.5% of the measured concentration. The continuous operating relative humidity range specified by the manufacturer is 15% to 90% (non-condensing). At higher humidity levels, water vapor will be gradually absorbed by the electrolyte solution, while at lower humidity levels, the cell will gradually dehydrate. The response time (time to 80% of perturbation) is approximately 35 seconds. A warm-up (equilibration) time of no less than 2 minutes is recommended.

2.1.4 Temperature Sensors

Thermal stratification is measured employing Telaire Inc. Model 1058T thermistor-based sensors with a range of 2 °C to 98 °C. EH&E's cumulative calibration records for these sensors show that, generally, the precision of the Telaire model 1058-T is better than ±0.1°C, and the accuracy better than 0.2 °C. The performance requirement specified in the BASE Protocol is ± 2 °C accuracy.

Additionally, the temperature sensors are checked with a Rotronic Instrument Company, Inc., digital thermo-hygrometer, Model PA-1, with a range of 0°C to 50°C, which is calibrated using known humidities from the head spaces of different salt solutions. The accuracy of the digital thermo-hygrometer is better than ± °C. The nominal operating temperature range for the Telaire temperature sensors is 2°C to 98°C, and 0 to 50°C for the digital thermo-hygrometer.

2.1.5 Relative Humidity Sensors

The relative humidity detectors employed are part of the aq-502 Indoor Environmental Monitor manufactured by Metrosonics. The aq-502's humidity sensor uses an electronic thin film capacitor. Increased humidity raises the dielectric constant of the capacitor proportional to the relative humidity in the air. The resistance of the open capacitor is measured and its value is converted by means of electronic circuitry into a voltage signal that is proportional to the relative humidity.

The output of the sensors is factory set to read zero volts at 0% RH and 1 V at 100% RH. The instrument response is nearly linear (maximum deviation from linearity is

3.0% RH). The instruments are rated for measuring the entire relative humidity range at operating temperatures between 0°C and 55°C. This meets the BASE method performance requirement of 20% to 90% RH.

The constant of the dielectric material is also temperature sensitive and contributes 0.04% RH/°C (0.4% RH for a 10°C change in temperature). According to the manufacturer, the accuracy of these RH sensors (including calibration inaccuracy, non-linearity effects, and repeatability) is ±3% at 25°C in the 0 to 100% RH range.

Cumulative calibration records of the aq-502 sensors kept at EH&E show accuracies and precisions better than ±2% RH. This complies with the BASE method performance requirement of ±5% RH for accuracy and ±5% RH for precision.

The nominal operating temperature range for the RH sensors is -5°C to 55°C. The response time (time to 90% of perturbation) is approximately 15 seconds. A warm-up (equilibration) time of no less than 30 seconds is recommended.

2.1.6 Illuminance (Light) Meter

Illuminance is measured using the aq-502 Indoor Environmental Monitor manufactured by Metrosonics. The light paddle uses a Photocell detector and operates in the 0 to 3000 Lux range. The accuracy of the instrument (quoted by the manufacturer) is ±1% of full scale, compared to the BASE method performance requirement of ±2 %.

2.1.7 Sound Level Meter

Sound levels are measured and recorded using the aq-502 Indoor Environmental Monitor manufactured by Metrosonics. The instrument uses an 8 mm omnidirectional microphone buffered by a high impedance FET input stage. The instrument is used with the "A" weighting characteristics in the 40-140 dB (decibel) range, 140 dB upper limit (BASE Protocol specifies 30 to 130 dB), an 85 dB criterion, and a 3 dB exchange rate. (These detection parameters correspond to particular settings of the instrument given in Section 2.2.) The aforementioned parameters define how the detected sound frequencies are weighted and the intensities averaged to define a net sound intensity perceived by the human ear. The parameters given have been selected to meet OSHA criteria.

The nominal operating temperature range for the omnidirectional microphone is 15°C to 50°C and the operating humidity range is 0 to 95% (non-condensing).

2.2 SET-UP AND MONITORING

2.2.1 Instrument Set-up

Each monitoring station consists of a cart with all sensors positioned at a height of 1.1 meter (m). A vertical stand holds temperature sensors positioned at 0.1 m, 0.6 m, 1.1 m, and 1.7 m heights above the floor level. Associated datalogger channel assignments and channel span settings are detailed in Table 2.1.

Table 2.1 Datalogger Channel Assignments and Channel Span Settings

Sensor	Logger Channel	Signal Range	Voltage Range
Carbon monoxide	Gas/Voltage 1	0 to 1000 ppm	0 to 100 mV *
Carbon dioxide	Built-In	0 to 5000 ppm	Internal (not user selectable)
Relative humidity	Built-In	0 to 100%	Internal (not user selectable)
Illuminance	Built-In	0 - 3000 Lux	Internal (not user selectable)
T1 (0.1 m)	Gas/Voltage 2	0 to 100° C	0 to 1V
T2 (0.6 m)	Gas/Voltage 3	0 to 100° C	0 to 1V
T3 (1.1 m)	Gas/Voltage 4	0 to 100° C	0 to 1V
T4 (1.7 m)	Gas/Voltage 5	0 to 100° C	0 to 1V

* Note: Select “CO” for range in the Metrosonics aq-502 software.

The aq-502 unit is placed on top of the sampling cart. The illuminance light paddle and the sound level sensing microphone sensor are plugged directly into the aq-502 unit and positioned at a 1.1 m height**.** The illuminance light paddle is positioned so that the sensing surface is facing up. The sound level sensing microphone sensor is attached to one of the vertical support posts on the cart and angled approximately 75 degrees toward the ceiling. The CO sensor is plugged into one of the channels on top of the aq-502 unit. Temperature sensors are positioned on the vertical temperature stratification stand at the height of 0.1 m, 0.6 m, 1.1 m, and 1.7 m above the floor level. If possible, the temperature stand should be situated at least one foot from the cart to avoid temperature affects generated from the sampling pumps on Wednesday of the sampling week.

The sampling carts are set up at four indoor sites: F1, F2, F3, and F5.

2.2.2 Log Book

A log book will be kept at each monitoring station. All procedures and observations conducted at the station, particularly readjustments of datalogger calibration points, will be recorded there. It is important that all field investigators record all site visits in the log book in order to eliminate investigator interference.

2.2.3 Initial Setup

The sensors are connected and tested for proper functioning on the Monday of the study week. The zero and span values of the CO_2 and CO sensors are also checked at this time (see Section 3.2). The time and date stamps on all data loggers are synchronized using both operator watches and the main computer clock.

2.2.4 Monitoring

Continuous monitoring at the indoor fixed sites is started on Monday evening or Tuesday morning[1] and continued through Thursday afternoon. The sites should be up and running at the latest by approximately 8:00 a.m. on Tuesday morning, and breakdown of the sites should occur between 4:30 and 5:30 p.m. on Thursday afternoon. During the monitoring period, instrument outputs (as displayed in the LED readout) are checked against standards at regular intervals as prescribed in the BASE Protocol. (see Section 3.2).

2.2.5 Downloading of Logged Data

Data is downloaded from all sites using MS-502 (Metrosoft Software Operation) at the end of each monitoring day; that is, at the end of the workday on Tuesday, Wednesday, and Thursday, or as access permits. The data downloaded from the aq-502 Monitors on Tuesday and Wednesday serve as a back-up to protect against data loss due to potential internal datalogger malfunctions.

After downloading of data on Thursday afternoon, the aq-502 Monitors must be turned off at all sites and the monitoring station disassembled for shipping.

NOTE: The degree to which the monitoring station must be disassembled will depend on the mode of transportation to be used for shipment to the next building.

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1 Investigators make every attempt to begin data logging on Monday afternoon; however, various factors, including drop shipment times and occupant issues, occasionally preclude these efforts.

3.0 CALIBRATIONS AND QUALITY CONTROL

3.1 MULTIPOINT CALIBRATION

The CO_2, CO, and temperature sensors must undergo multipoint calibrations before and after each seasonal (summer/winter) BASE Study. A humidity sensor multipoint calibration check is also performed at this periodicity. For the humidity sensor, light meter, and noise dosimeter, multipoint calibrations are performed annually by the manufacturer. The aq-502 is pre-programmed to give outputs in the units of ppm for CO_2 and CO, and Lux for illuminance. EH&E programs the aq-502 gas/voltage channels to match the temperature sensor calibrations by entering a 0°C and a 100°C voltage. Each temperature sensor is permanently assigned to that channel, which is programmed uniquely to its calibration points, and remains throughout each study so that re-entering calibration data for each building is not necessary. The multipoint calibrations (no fewer than three points for RH and five points for temperature) are used to establish precision values for the sensors over a range of concentrations. Table 3.1 details the ranges of interest with respect to multipoint calibration.

Table 3.1 Ranges of Interest with Respect to Multipoint Calibration

Parameter	Minimum Value	Maximum Value
Carbon dioxide	0 ppm	approx. 2,000 ppm
Carbon monoxide	0 ppm	approx. 100 ppm
Relative humidity	approx. 0 %	approx. 90 %
Temperature	approx. 0°C	approx. 40°C

ppm = parts per million

3.1.1 CO_2 Sensors

To perform multipoint calibration, the CO_2 sensor is sealed in a flow-through cell and exposed, in sequence, to no fewer than four gas mixtures of known CO_2 concentrations (e.g., 0 ppm, 500 ppm, 1,000 ppm, and 1,500 ppm). As the aq-502 uses an active sampling method (an internal pump draws air past the sensor), tedlar sample bags filled with calibration gas may be used to connect to the sample line. An alternate method may also be used in which the calibration gas is applied directly from the cylinder

through internal tubing directly to the CO_2 sensor. The tubing is accessible via a hand-hole on the side of the unit. This arrangement allows calibrating gas to feed the sensor directly and bypass the internal pump. The linearity check will be considered satisfactory if a correlation coefficient equal to or better than 0.99 is attained. (The instrument linearity frequently exceeds the gas concentration accuracy. This proves to be more of a test of the manufacturer's analysis of the calibration gas.) The mean square deviation from the linear correlation(s) for each sensor will be established from this data.

NOTE: Since the expected (manufacturer specified) accuracy of the readings is approximately 3%, the mean square deviation is 50 ppm**,** and the specified linear range is 0 ppm to 5,000 ppm, the highest calibration gas concentration range must be kept at or below 4,550 ppm (5,000 x 0.95 - 2s). This is an uncommonly high CO_2 level, so calibrations are not routinely performed in this range.

3.1.2 CO Sensors

The calibration and spanning of the CO sensors require particular care to obtain accurate and precise measurements. EH&E's experience with the sensors is that they are highly linear in the range specified by the manufacturer ($R > 0.99$ for 0 ppm to 1000 ppm); however, the accuracy of the measurements is affected by temperature and barometric pressure. This effect is more pronounced at concentrations near the detection limit of the sensor, which are the conditions normally found in the indoor environment.

Before and after each seasonal BASE study, each CO sensor must be checked for linearity of response. This check will be conducted by exposing the sensor in sequence to no fewer than four gas mixtures of known CO concentration (e.g., 0 ppm, 4 ppm, 10 ppm, 20 ppm). The linearity check will be considered satisfactory if a correlation coefficient equal to or better than 0.99 is attained. The mean square deviation from the linear correlation(s) will be established for each sensor from this data. The linearity check will be repeated after the completion of each seasonal BASE study.

3.1.3 Relative Humidity Sensors

Before and after each seasonal BASE study, each RH sensor must be checked for linearity of response. The instrument is adjusted annually by the manufacturer using a 3-point calibration. Because the units are not sent to the manufacturer between the winter and summer studies, EH&E performs a minimum 3-point calibration check using a NIST traceable standard to verify compliance to BASE criteria.

3.1.4 Temperature Sensors

Before and after each seasonal BASE study, each temperature sensor will be calibrated and checked for linearity of response. This check will be conducted by inserting each sensor into an aluminum block next to a National Institute for Standards and Technology (NIST) calibrated precision mercury thermometer. With the aluminum block immersed in a water bath equipped with a variostat heating element and pump, five or more temperatures will be tested (e.g., 10°C, 15°C, 20°C, 25°C, 30°C). The linearity check will be considered satisfactory if a correlation coefficient equal to or better than 0.999 is attained. The mean square deviation from the linear correlation (s) will be established for each sensor from this data.

3.1.5 Illuminance Meter

This instrument is factory-calibrated only.

3.1.6 Sound Level Sensor

The sensor is calibrated in the field prior to each three-day monitoring period against either a 114 dB (Quest Technologies) or 102.2 dB (Metrosonics, Inc.) source. Both the Quest noise calibrator and the Metrosonics calibrator are annually factory calibrated.

3.2 ZEROING AND SPANNING

The stability and accuracy of the CO_2 and CO sensors are checked daily during the monitoring period by measuring their responses to calibration gases (air-CO_2 and air-CO mixtures) of known composition. A “zero and span” check is the measurement of the

response of a linear instrument to two gases of known composition to ascertain that the instrument response has not changed beyond the standard deviation set by its calibration.

A zero and span check of all fixed-site CO_2 and CO sensors is performed on Monday of the study week and on the mornings of Tuesday, Wednesday, and Thursday. All fixed site dataloggers will remain in the logging mode while performing the zero and span check.

To verify the response of the CO_2 sensor, a hydrocarbon-free air is used as the zero gas; the span gas is a gas mixture with a CO_2 concentration approximating the highest values expected in an indoor environment (i.e., 1,000 to 1,500 ppm CO_2).

To verify the response of the CO sensors, hydrocarbon-free air is used as the zero gas and the span gas is air mixed with CO in the range of 10 to 25 ppm.

All zero and span gases are contained in compressed gas cylinders equipped with pressure regulators and flow meters. All cylinders are fixed within a mobile cart and are transported to the monitoring sites where sensors must be zeroed and spanned. The outlet from each gas cylinder is connected to the flow meter, and the flow rate is adjusted to approximately 1 liter per minute. Once the flow rate is adjusted, the outlet from the flow meter is connected to the inlet to the sensor to be zeroed or spanned. The flow rate is then adjusted again, if necessary.

The BASE Protocol specifies primary and secondary ranges of deviations from calibration response values for each instrument. If zero and span or calibration check readings fall within the primary range, the instrument is considered to be “in spec.” If one of the two sensor readings (zero or span) or a calibration check falls outside of the primary range but within the secondary range, the continued use of the instrument must be justified, and the data obtained with the sensor or instrument must be appropriately flagged. If the sensor or instrument response falls outside the limits set by the secondary range, the sensor or instrument must be replaced. Primary and secondary ranges for each parameter are detailed in Table 3.2.

Table 3.2 Primary and Secondary Ranges for Each Parameter

Parameter	Primary Range[1]	Secondary Range[2]
Temperature	± 1.0°C	± 2.0°C
Relative humidity	± 5% RH	± 7% RH
Carbon dioxide	zero ± 50 ppm span ± 75 ppm	zero ± 75 ppm span ± 150 ppm
Carbon monoxide	zero ± 2 ppm span ± 3 ppm	zero ± 3 ppm span ± 5 ppm
Noise	± 4 dB	± 6 dB
Illuminance	not applicable	not applicable
Sample flows	± 10%	± 15%

[1] Instrument is "in spec" if below this value.
[2] Below this value requires justification for continued use; above this value renders data unusable.

4.0 SHIPPING AND STORAGE PROCEDURES

When shipped from city to city, the aq-502 Monitor and its accessories, along with the external temperature apparatus for each site, must be packed inside padded cases. While in storage or transport, the instrument will not be exposed to temperatures outside the manufacturer's specified range of -40°C to 70°C. When transported by the field team, such as from one building to another within a single city, the sensors may remain installed on the sampling carts, but must be protected with suitable dust covers and impact padding.

5.0 RECORDS AND DATA DOWNLOADING

Data downloading and storage will be conducted in accordance to the procedures outlined in the *EPA Large Buildings Studies Integrated Protocol*, (RTI/4479/013), Section 7.1.2: Management of Real-Time Monitoring Data.