AQ-SPEC
Air Quality Sensor Performance Evaluation Center

# Laboratory Evaluation of Low-Cost Air Quality Sensors

## Laboratory Setup and Testing Protocol

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## TABLE OF CONTENTS

1. BACKGROUND ..... 2
1.1. "LOW-COST" AIR QUALITY SENSORS ..... 2
1.2. AIR QUALITY SENSOR PERFORMANCE EVALUATION CENTER (AQ-SPEC) ..... 2
1.3. SENSOR SELECTION CRITERIA FOR AQ-SPEC'S LABORATORY EVALUATION ..... 3
2. METHODS ..... 3
2.1. LABORATORY CHAMBER SYSTEM ..... 3
2.2. ZERO-AIR GENERATION SYSTEM ..... 5
2.3. PM SENSORS TESTING ..... 6
2.3.1. OUTER CHAMBER ..... 6
2.3.2. PARTICLE GENERATORS ..... 7
2.3.3. PARTICLE MONITORS ..... 8
2.4. GAS SENSORS TESTING ..... 9
2.4.1. INNER CHAMBER ..... 9
2.4.1.1. MODE A ..... 10
2.4.1.2. MODE B ..... 10
2.4.2. GAS MONITORS ..... 11
2.4.3. VOC SENSORS TESTING ..... 12
2.5. POLLUTANT CONCENTRATION SET-POINTS AND SELECTION CRITERIA ..... 12
2.6. CHAMBER SYSTEM SOFTWARE ..... 13
2.7. SENSORS COMMUNICATION WITH CHAMBER SYSTEM SOFTWARE ..... 15
3. SENSOR EVALUATION ..... 15
3.1 LABORATORY EVALUATION PARAMETERS ..... 15
3.1.1. INTRA-MODEL VARIABILITY ..... 16
3.1.2. ACCURACY ..... 17
3.1.3. PRECISION ..... 18
3.1.4. DETECTION LIMIT ..... 18
3.1.5. LINEAR CORRELATION COEFFICIENT ($R^2$) ..... 19
3.1.6. INTERFERENTS ..... 19
3.1.7. CLIMATE SUSCEPTIBILITY ..... 20
3.1.8. DATA RECOVERY ..... 20
3.1.9. SENSOR DECAY AND DEGRADATION ..... 20
3.1.10. BASELINE DRIFT ..... 20
3.1.11. RESPONSE TO LOSS OF POWER ..... 21
3.2. LABORATORY TESTING PROCEDURES ..... 21
3.2.1. PM SENSOR LABORATORY TESTING PROCEDURE ..... 21
3.2.1.1. OUTER CHAMBER AND PM SENSORS PREPARATION ..... 21
3.2.1.2. AEROSOL ATMOSPHERE AND TESTING ..... 22
3.2.2. GASEOUS SENSOR LABORATORY TESTING PROCEDURE ..... 23
3.2.2.1. INNER CHAMBER AND GASEOUS SENSORS PREPARATION ..... 23
3.2.2.2. GASEOUS ATMOSPHERE AND TESTING ..... 24
3.3. DATA ANALYSIS ..... 25
4. STUDY LIMITATIONS ..... 25
REFERENCES ..... 26
APPENDIX ..... 27

## 1. Background

### 1.1. "Low-cost" air quality sensors

Manufacturers have recently begun marketing low-cost air quality sensors to measure air pollution, and considering how fast the air monitoring sensor technology is evolving, it is likely that the availability of such sensors in terms of both type and numbers will continue to grow in the near future. These devices, provided they produce reliable data, can significantly augment and improve current ambient air monitoring capabilities that now predominantly rely on more sophisticated and expensive fixed-site federal-reference monitoring devices and methods. In particular, these devices can be deployed near specific sources to better characterize local levels of air contaminants or over a wider geographic area to identify spatial and temporal trends. Given their "low-cost", these sensors are becoming an attractive means for local environmental groups and individuals to independently evaluate air quality. The new approach is receiving acknowledgement from the U.S. EPA and will likely introduce a paradigm shift to supplement traditional air monitoring by air regulatory agencies with community-based monitoring using air monitoring sensors. Due to their "low-cost" and ease of use, such devices also have the potential of becoming highly effective tools for introducing and engaging students and community groups in air quality matters.

There are, however, no independent objective means by which these devices can be evaluated, and data from these monitors are usually accepted at face value with no opportunity to evaluate their accuracy and overall quality. In fact, preliminary tests performed in the U.S. and in Europe seem to suggest that many of the commercially available air monitoring sensors have poor to modest reliability, do not perform well in the field under ambient conditions, and do not typically correlate well with data obtained using "standard" measurement methods employed by regulatory agencies. Poor quality data obtained from unreliable sensors, especially that in conflict with data obtained from traditional and more sophisticated monitoring networks, may not only lead to confusion but may also jeopardize the successful evolution of this "low-cost" sensor technology. Therefore, there is an urgent need to better characterize the actual performance of air monitoring sensors as well as to educate the public and users about the potential and limitations of these devices.

### 1.2. Air Quality Sensor Performance Evaluation Center (AQ-SPEC)

In an effort to provide the public with much-needed information about the actual performance of commercially available "low-cost" sensors, the South Coast Air Quality Management District (SCAQMD) has established the Air Quality Sensor Performance Evaluation Center (AQ-SPEC) to perform thorough performance characterization of currently available sensors using both field- and laboratory-based testing. In the field, air quality sensors are operated side-by-side with Federal Reference Methods and Federal Equivalent Methods (FRM and FEM, respectively) that are routinely used to measure air pollutants concentrations for regulatory purposes (see Appendix). All sensors are evaluated in triplicates and for a period of two months to provide better statistical information of overall performance. In the lab, a state-of-the-art characterization chamber is used to challenge the sensors with known concentrations of different particle and gaseous pollutants under controlled environmental conditions.

This document describes the laboratory testing procedures used by SCAQMD Staff to evaluate the performance of commercially available "low-cost" air quality sensors under known laboratory chamber conditions of relative humidity (RH), temperature (T), pollutant and interfering species concentrations. All

data collected, documentation developed, and testing results obtained during this project are organized and posted online as part of the AQ-SPEC website (www.aqmd.gov/aq-spec) and made available for free to educate the public on the capabilities of commercially available air quality sensors and their potential applications. Sensor-related events and workshop information are also posted on this website.

### 1.3. Sensor selection criteria for AQ-SPEC's laboratory evaluation

Sensors are selected for testing at AQ-SPEC (both field and laboratory) based upon the following criteria:

- The sensor shall be commercially available.
- The sensor shall measure one or more of the National Ambient Air Quality Standards (NAAQS) criteria pollutants, air toxics, pollutants of concern and non-air toxics. Examples of the targeted gases and particles are carbon monoxide (CO), ozone ($O_3$), nitrogen oxides ($NO_x$), particulate matter (PM), volatile organic compounds (VOCs), hydrogen sulfide ($H_2S$), and methane ($CH_4$).
- The sensor shall have high sensitivity at ambient level and low concentrations.
- The sensor shall provide real- or near-real time measurements. In order to be considered for evaluation, a sensor must have the ability to either store data internally or log data to a computer via a supplied software or have a serial port output. Logging data to a cloud based server is also acceptable. Sensors store data in other ways might be accommodated, provided confirmation by AQ-SPEC team.
- The sensor shall have the capability of continuously running for at least two months, using AC or DC power.
- The market cost of the sensor shall be less than $2000. If a device presents as a multi-pollutant sensor box, then the cost per pollutant type (individual sensor) should be less than $2000.

Sensors are first evaluated in the field at one of SCAQMD's fixed air monitoring stations for two months. Depending on the field testing results, sensors, which have shown acceptable performance (correlation coefficient $R^2 > 0.4$-$0.5$), are brought back to the laboratory for chamber testing.

## 2. Methods

### 2.1. Laboratory chamber system

A chamber system, designed by AQ-SPEC, developed and integrated by American Ecotech/AmbiLabs (Warren, RI), has been installed inside the SCAQMD Chemistry Laboratory (Figures 1a-c and d).

The chamber system consists of:

i) a professional-grade environmental test chamber (G-Series Elite, model GD-32-3-AC, Russells, Holland, MI) capable of accurately creating and maintaining a wide range of temperature and relative humidity conditions. This includes a stainless steel rectangular-shaped enclosure (here referred to as "outer chamber"), a heating/cooling system for controlling the test temperature, a humidifier/de-humidifier for varying the relative humidity

ii) a custom-made Teflon-coated stainless steel cylindrical-shaped enclosure (here referred to as "inner chamber") installed inside the "outer chamber" and used for gas sensors testing;
iii) a dry, gas- and particle-free air ("zero-air") generation system, comprised of a series of scrubbers;
iv) two particle generators (model AGK 2000 by PALAS and model SAG 410/U by TOPAS, Germany);
v) a dynamic dilution calibrator (model T700 U by Teledyne API, San Diego, CA);
vi) an array of FRM/FEM and BAT (Best Available Technologies) instruments;
vii) an integrated computer software that controls the various operating/experimental parameters and environmental (i.e. temperature and relative humidity) set-points.

**Figures 1a-c**. AQ-SPEC's laboratory chamber system

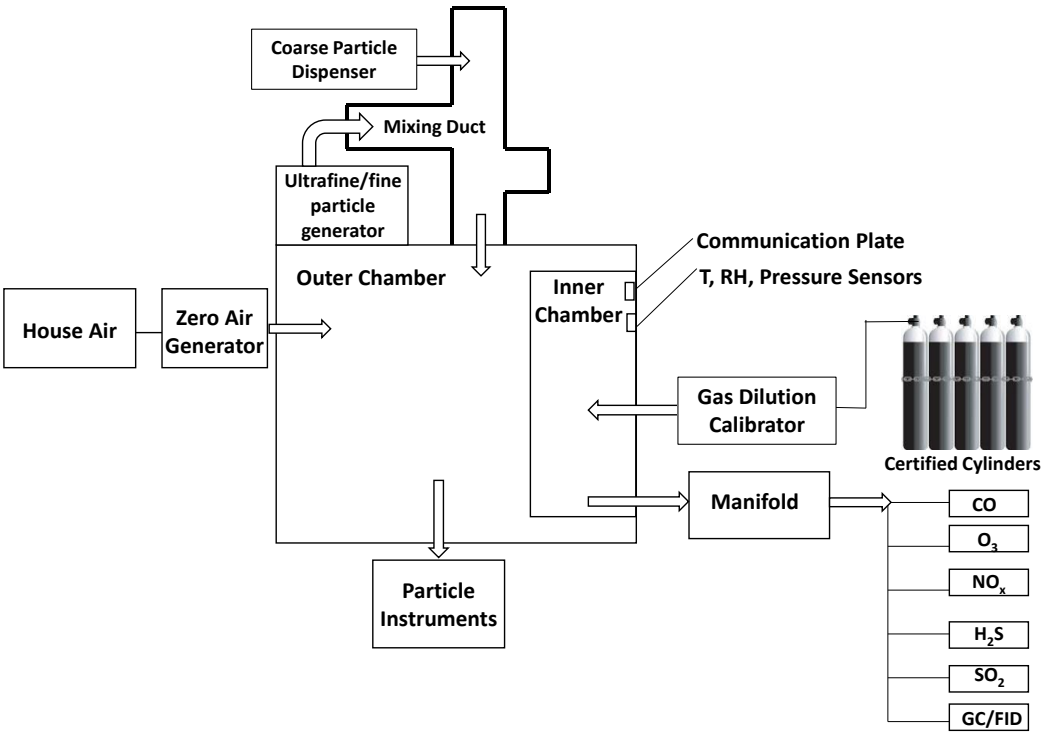



**Figure 1d.** Schematic of AQ-SPEC's laboratory chamber system

## 2.2. Zero-air generation system

This system is comprised of a series of scrubbers used to remove gaseous and particulate impurities from the supplied laboratory compressed dried air (see Figure 2). As shown in Figure 2, from right to left (direction of house air flow), the scrubbers used in this system are:

i) one heated catalyst scrubber for the removal of carbon monoxide (CO)
ii) two scrubbers of activated carbon to remove VOCs and $NO_2$
iii) two scrubbers of sodium permanganate ($NaMNO_4$) impregnated on porous alumina to remove $H_2S$, $SO_2$, $NO_2$, NO, and HCHO
iv) one cylinder of manganese dioxide/copper oxide ($MNO_2$/CO) catalyst to remove ozone
v) one cylinder of 13X molecular sieve to remove moisture
vi) two cylinders of calcium sulfate ($CaSO_4$) in series to further dry the house air (outside compressed and dried air)
vii) one in-line HEPA filter to remove particulate impurities

**Figure 2.** Dry, gas- and particle-free air system (or zero-air system)

The output of this system is dry, gas- and particle-free air that is used for the dilution of the test particles or gases to achieve the target pollutant(s) concentrations inside the chamber. The performance of the zero-air generation system is validated by the FEM/FRM instruments. When the chamber is purged with zero-air, readings on the reference instruments are zero or close to zero. In addition, the zero-air system is regularly maintained according to the operation procedures.

Specifically, this zero-air is used in:

i) the T700U dilution calibrator for the dilution of gases supplied by certified compressed gas cylinders;
ii) the PALAS particle generator to aerosolize the salt solution inside the glass bottle;
iii) the TOPAS particle generator to direct the particles into the mixing duct;
iv) the outer and inner chambers when they are flushed and conditioned under controlled temperature and relative humidity.

## 2.3. PM sensors testing

### 2.3.1. Outer chamber

The rectangular-shaped outer chamber [38" (width) x 38" (height) x 54" (depth) with a volume of 1.1 $m^3$] is made of stainless steel and is used to conduct laboratory performance evaluation tests of particle sensors. The bottom of the outer chamber has a hollow shape to allow easy drainage of any condensate towards a drain at the deepest point. This drain helps to quickly evacuate dehumidified condensation during rapid temperature changes. A set of two fans installed in the rear wall of the outer chamber, behind the upper wall perforations, generates a circular airflow in the chamber with the air flowing in from the bottom first through the cooling and dehumidifying coils and then passing through the heating elements. This air movement mechanism provides for uniform mixing inside the outer chamber. All parts are either made of stainless steel or coated with Teflon or other inert material to help prevent unwanted chemical reactions of gases together with the condensing humidity on the coils and the dehumidifier. The outer chamber is capable of reaching temperatures (T) between -32 °C (-26 °F) and +177 °C (350 °F) and relative humidity (RH) levels ranging from 10% to 95%.

During a typical PM sensor experiment, T and RH conditioned zero-air is mixed inside the outer chamber with dry particles. Frequency and duration of dry artificial aerosol injection is controlled to provide the desired particle mass/number concentration in the desired test particle size range. The outer chamber is operated under a small positive pressure and the excess air is dumped through the chamber exhaust system into the laboratory ventilation system. PM sensors are typically tested in triplicates and placed on Teflon trays on the right-hand side of the outer chamber prior to testing (Figure 3).

**Figure 3.** Inside view of the outer chamber;
PM sensors are placed on three Teflon trays (in white) for testing

### 2.3.2. Particle generators

The chamber is equipped with two particle generators that allow generating particles of various sizes and types. An aerosol generator made by PALAS (model AGK 2000; Karlsruhe, Germany) is used to produce ultrafine and fine particles from various solutions (e.g. potassium chloride, sodium chloride of known density and shape factor, Sigma-Aldrich, St Louis, MO) and suspensions (e.g. monodisperse polystyrene of various sizes , 200 nm, 1, 2, 10µm, Sigma-Aldrich, St. Louis, MO)) in de-ionized water (Figure 4a). A specially developed nozzle prevents the crystallization of the salt crystals at the nozzle outlet, thus ensuring that the concentration and size distribution of the test aerosol is stable, consistent throughout the testing period and reproducible between different experiments under the same testing conditions. Particle size and distribution can be adjusted within a range of approximately 5 nm to 10 µm, monodisperse or polydisperse, depending on the type of particles used and the concentration of the solution/dust powder. The generated particles are fed into a dryer stage and then injected into a mixing duct, where the particle loaded air from the dryer is mixed with particle-free laboratory room air (Figure 4c). A portion of the air is exhausted from the mixing chamber through a filter while the remaining air is fed through the center tube into the outer chamber. A solid aerosol dispenser made by TOPAS (model SAG 410/U, Dresden, Germany) is used to dispense large, coarse and fine particles using dust powder (e.g. ISO 12 103, A4 Coarse by TOPAS, Arizona road dust type) (Figure 4b). Particles are directed into the testing chamber in a similar way. During these experiments, the particle sensors are placed on sensor trays mounted on the inner chamber base (on the right-hand side of the outer chamber) that carries the sensors communication plate (Figures 4d-e). Inlet probes are installed at the base of the outer chamber and connected to various PM monitoring devices (reference instruments) for monitoring particle mass concentration and size distribution.

**Figure 4a**. Ultrafine/fine particle generator

**Figure 4b.** Large/coarse/fine particle dispenser

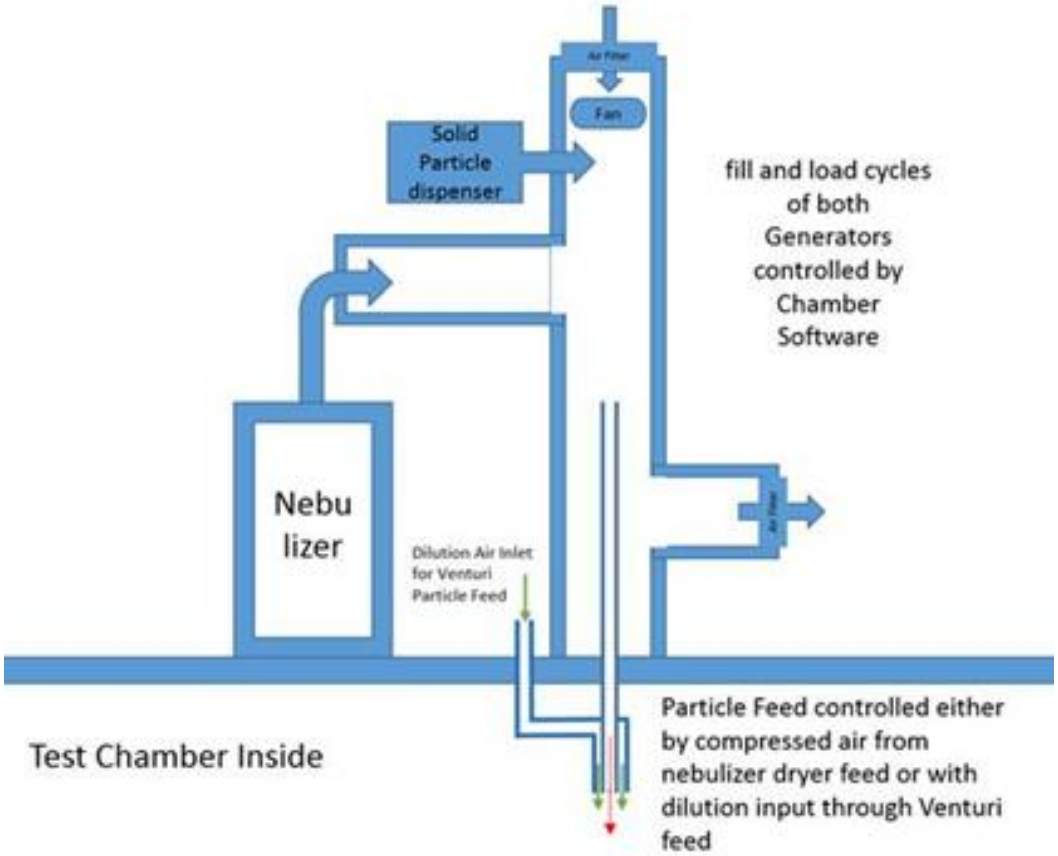
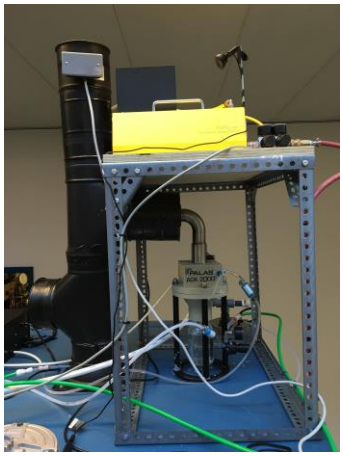



**Figure 4c.** Schematic of particle generation and dispensing system



**Figures 4d-e.** Particle generators (d) and particle instruments inlet probes (e)

2.3.3. Particle monitors

The reference (FEM or non-FEM) continuous and semi-continuous particle monitors used to conduct particle size distributions and mass concentration measurements are listed below:

- Dust Monitor by GRIMM (model EDM180, Ainring, Germany): The EDM 180 spectrometer provides high-resolution real-time aerodynamic measurements of $PM_{10}$, $PM_{2.5}$, $PM_{1.0}$, TSP and $PM_{coarse}$ particles. The EDM 180 measures light-scattering and is designated as class III equivalent method EQPM-0311-195 by the U.S.EPA.
- Fast Mobility Particle Sizer Spectrometer (FMPS) by TSI (Model 3091, Shoreview, MN): The FMPS 3091 spectrometer measures aerosol particles in the range from 5.6 to 560 nm, with a total of 32 channels of resolution (16 channels per decade). The FMPS spectrometer uses an electrical mobility technique with multiple, low-noise electrometers for particle detection, and enables particle size distribution measurements with one-second resolution.
- Aerodynamic Particle Sizer (APS) by TSI (Model 3321): The APS 3321 spectrometer provides high-resolution, real-time aerodynamic measurements of particles from 0.5 to 20 µm. The APS measures light-scattering intensity in the equivalent optical size range of 0.37 to 20 µm.

## 2.4. Gas sensors testing

### 2.4.1. Inner chamber

The inner chamber is a cylindrical-shaped [12" (radius) & 15" (height) with a volume of 0.11 $m^3$] enclosure made of Teflon-coated stainless steel and used only to conduct the laboratory evaluation of gas sensors (Figure 5). A duplicate of this inner chamber made of stainless steel, but not coated with Teflon, is exclusively used for VOC sensors testing. A known concentration of one or more gaseous pollutants (test atmosphere) at a controlled flowrate is either a) diluted inside a dilution calibrator and subsequently supplied into the inner chamber (Mode A), or b) diluted inside the inner chamber with zero-air that has been conditioned into the outer chamber and introduced into the inner chamber (Mode B). Test gases include CO, NO, $NO_2$, $O_3$, $SO_2$, $H_2S$, and VOCs. The T700 Dynamic Dilution Calibrator (Teledyne API, San Diego, CA) is used to generate calibration gas mixtures by mixing gases of known concentrations from a certified compressed gas cylinder with a diluent gas (zero air). Using Mass Flow Controllers (MFCs), the T700 calibrator creates exact ratios of diluent and source gas by controlling the relative rates of flow of the various gases, under conditions where the temperature and pressure of the gases being mixed (and therefore the density of the gases) is known. This dilution process is dynamic. The T700's CPU keeps track of the temperature and pressure of the various gases and receives data on actual flow rates of the various MFCs in real time so that the flow rate control can be constantly adjusted to maintain a stable output concentration. Once the exact concentrations of all gases are programmed into the dilution calibrator, the T700 creates an exact output concentration of any of the gas components (see Mode A below). The total zero-air diluted gas flow through the inner chamber is 12 L/min. For a 110 L volume of the inner chamber, the gas molecule residence time *t* in the chamber is calculated by

$$t = \frac{V}{Q} = \frac{110\ L}{12\ \frac{L}{min}} = 9.16\ min$$

Where,
V is the volume of the inner chamber
Q is the total zero-air diluted gas flow through the chamber

To reach a steady-state condition inside the inner chamber, 2-3 residence times are needed for a total of about 19 to 28 minutes.

**Figure 5.** Inner chamber installed inside the outer chamber;
This configuration is exclusively used for testing gaseous sensors

2.4.1.1. Mode A

Dynamic gas dilution is performed by the dilution calibrator. Gas (or a mixture of gases) from certified compressed gas cylinder(s) (or generated by the T700U calibrator in case of ozone) is introduced into the calibrator where it is diluted with zero-air. Subsequently, the zero-air diluted gas is introduced into the inner chamber at the desired concentration (Figure 6a). This mode of operation is used when a relatively small amount of gas and a short stabilization period are required to reach the desired gas testing conditions. However, chamber T and RH cannot be controlled when using this operation mode. Mode A is used to run "simple" tests, under laboratory T and RH conditions, to confirm that proper set-up (e.g. wire connections and sensors installation) have taken place and more detailed sensors testing is ready to commence using Mode B (described in the next section).

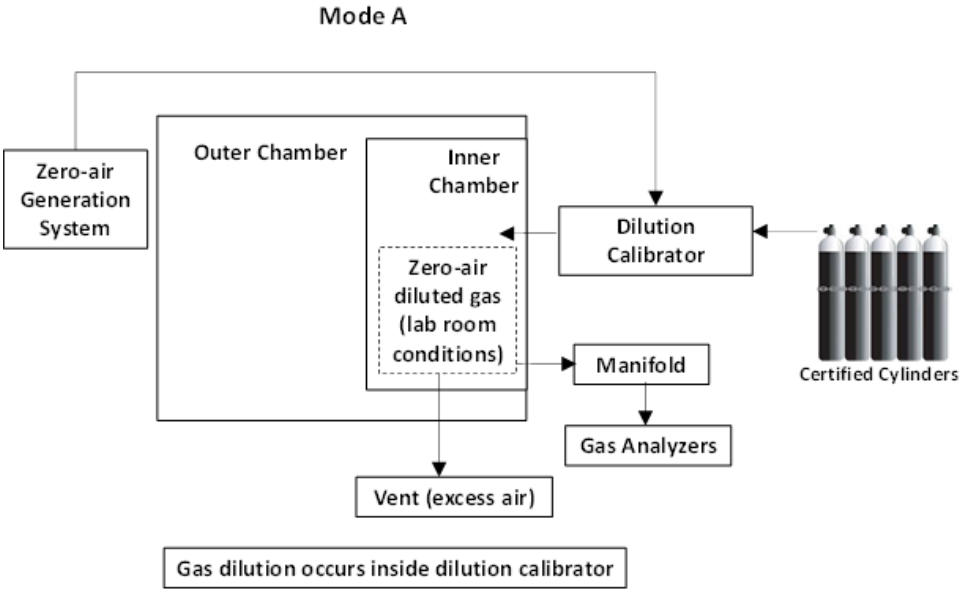



**Figure 6a.** Schematic of "Mode A" experimental setup

2.4.1.2. Mode B

Dynamic gas dilution is controlled by the dilution calibrator, but it uses an external mass flow controller (MFC) and a vacuum flow control box. Gas from a certified compressed air cylinder is introduced into the

inner chamber from the calibrator's output. Dilution zero-air is drawn from the outer chamber through the MFC into the inner chamber (Figure 6b). This is a more complex operation mode where T and RH in the zero-air can be controlled to mimic the target environmental conditions inside the inner chamber.

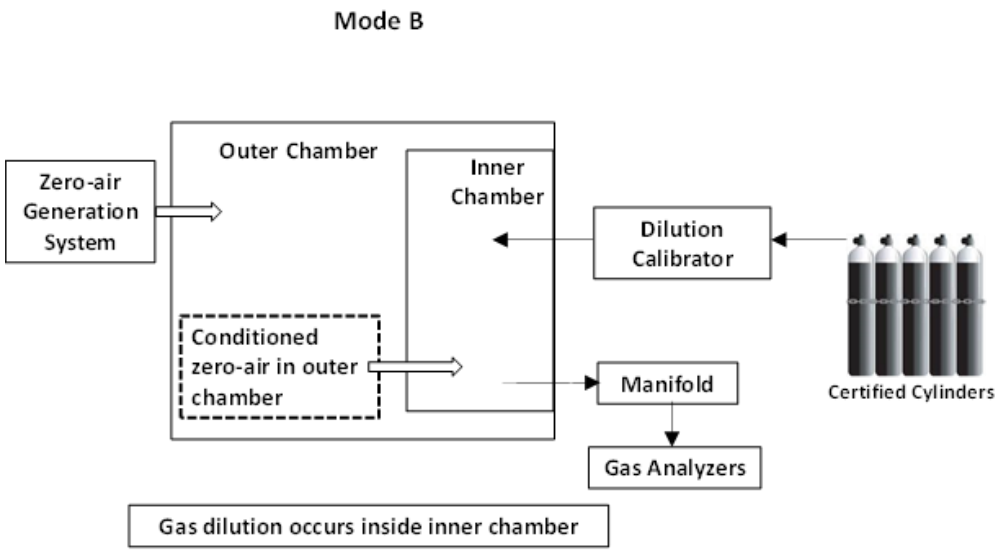



**Figure 6b.** Schematic of "Mode B" experimental setup

2.4.2. Gas monitors

The reference (FRM or BAT) continuous gas monitors used to conduct gas concentrations measurements in laboratory evaluation are:

- EC9830T Trace CO Analyzer by American Ecotech: The EC9830T is a non-dispersive infrared photometer that measures CO using gas filter correlation (GFC). The EC9830T is designated as a reference method RFCA-0992-088 by the U.S. EPA (40 CFR Part 53).
- Serinus 40 $NO_X$ Analyzer by American Ecotech: The Serinus 40 uses gas phase chemiluminescence detection to perform continuous analysis of NO, total $NO_X$ and $NO_2$. The Serinus 40 is designated as a reference method RFNA-0809-186 by the U.S. EPA (40 CFR Part 53).
- Serinus 10 $O_3$ Analyzer by American Ecotech: The Serinus 10 is a Non-Dispersive Ultra-Violet (UV) photometer which alternately switches a selective $O_3$ scrubber in and out of the measuring stream and computes the ratio of transmitted light giving a measure of $O_3$ concentration. A mercury vapor lamp is used as the light source. The Serinus 10 is designated as an equivalent method EQOA-0809-187 by the U.S. EPA (40 CFR Part 53).
- EC9850T $SO_2$ Analyzer by American Ecotech: The EC9850T uses UV fluorescent radiation technology to detect $SO_2$. The EC9850T is designated as an equivalent method EQSA–0193-092 by the U.S. EPA (40 CFR Part 53).
- Serinus 55 $H_2S$ Analyzer by American Ecotech: The Serinus 55 uses UV fluorescent radiation technology combined with an external thermal converter to detect $H_2S$.
- Methane/Non-Methane/Total Hydrocarbon Analyzer (Model 200T-S) by VIG Industries: The 200T-S measures concentrations of hydrocarbons in gas mixtures in the air and can separate the methane component from the non-methane component by using a GC column.

### 2.4.3. VOC sensors testing

A duplicate inner chamber (110 L) made of stainless-steel, but not coated with Teflon, is used to conduct VOC sensor testing. Two different types of compressed VOC gas cylinders are used in combination with zero-air to generate VOC mixtures of target concentrations. One cylinder contains 10 ppm of benzene and the other contains a mixture of benzene, 1,3-butadiene, ethane, and tetrachloroethylene at 10 ppm each. VOCs from the cylinder will be diluted with zero-air inside the dynamic dilution calibrator to generate concentrations from 1 ppb to 50 ppb. Subsequently, the diluted VOC output is introduced into the stainless steel chamber, where the VOC sensors being tested are situated. At least one VOC instrument (e.g. a GC/FID, or a VIG T200 methane/non-methane hydrocarbon analyzer) is used as the reference.

To address the potential safety and health risks of handling these gases, a gas cabinet (model 7200, Safety Equipment Corporation, Belmont, CA) is connected to the laboratory exhaust venting and sprinkler system and fitted with a benzene-leak detection sensor/alarm and a vent flow meter.

## 2.5. Pollutant concentration set-points and selection criteria

Concentration set-points are selected to represent pollutant levels from “very low” to “very high”. The goal is to evaluate sensor’s performance in different concentration ranges and compare with what the sensor manufacturer claims. Results from these experiments will confirm performance parameters such as accuracy, lower detection limit and linear correlation. The NAAQS standards as well as the chamber system capability in generating specific gas and particle normal and extreme test atmospheres and the reference analyzers’ detection ranges have been considered in designing the selection criteria.

The “very low” level is chosen to represent a pollutant concentration below the U.S. EPA NAAQS requirement. It is also close to the lowest concentration the chamber could generate or the reference analyzer could detect. The “low” and “medium” pollutant levels are similar to the average ambient pollutant concentration level and 50% above the average ambient pollutant concentration level, respectively. The “high” pollutant level is at least 100% higher than the average NAAQS standard level. The “very high” pollutant level is close to the maximum concentration the chamber could generate or the reference analyzer could accurately detect. The following table shows indicative concentration set-points of some specific test pollutants.

**Table 1.** Indicative pollutant concentration set-points

| Pollutant / Level | **PM** (µg/m$^3$) | **CO** (ppm) | **$O_3$** (ppb) | **$NO_2$** (ppb) | **$SO_2$** (ppb) |
|---|---|---|---|---|---|
| **Very Low** | 10 | 1 | 30 | 30 | 30 |
| **Low** | 15 | 4 | 50 | 50 | 50 |
| **Medium** | 50 | 7 | 90 | 70 | 70 |
| **High** | 150 | 15 | 150 | 100 | 150 |
| **Very High** | 300 | 20 | 250 | 200 | 300 |

## 2.6. Chamber system software

A custom-developed software by American Ecotech is used to automatically and remotely control and operate the chamber and all reference instruments. This software allows for the design of extensive sensor testing experiments using programmed sequences and consists of two main integrated components, i) the sequence runner and ii) the winAQMS Data Acquisition and Control System (Figures 7 and 8).

The sequence runner is used to:

i) set the chamber T and RH during either a gas or an aerosol atmosphere test in the inner or outer chamber, respectively
ii) program and run the small or large size aerosol sequences (or "recipes") through the PALAS or TOPAS generators, respectively. "Recipes" are prepared by pre-setting the frequency and duration of aerosol injection into the chamber to produce particles with known concentrations and size distributions
iii) set and run the flushing of either the outer or inner chamber with zero-air between experiments when switching from one aerosol/gas atmosphere to another, or for an extended period of time when flushing the chamber with zero-air after chamber cleaning, maintenance and/or servicing

Experimental sequences can be programmed to load and run for extended periods of time such as multiple days of continuous chamber operation on a 24/7 fashion. Sequences can be logged, saved, re-loaded when needed, and can be exported as .txt or .csv files when they must be documented in testing reports and procedures (See Appendix Table A3 and Figure A1).

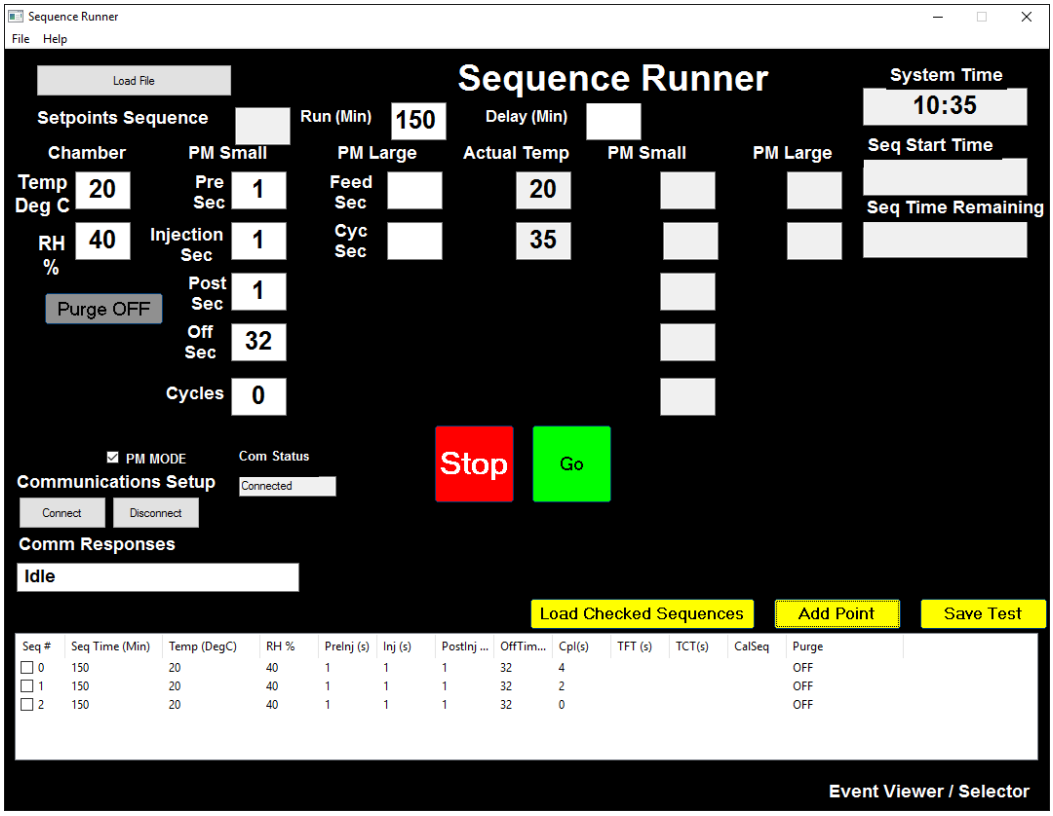



**Figure 7.** Sequence runner software interface

WinAQMS Data Acquisition and Control System is a windows-based data collection and control software which provides full control over the chamber system, enabling readings to be recorded, automatic calibrations to be performed and system errors to be monitored. WinAQMS interfaces to analyzers via a RS232 multi-drop serial link, through a USB link or via TCP/IP network link. This allows it to collect data directly from the instruments in digital format, thus eliminating digital to analog and analog to digital conversion errors. WinAQMS uses four main software components:

- Client: the user interface used to view data and alter the setup of the logger components
- Server: collects, stores and manages data collection
- Data server: responds to requests for data
- Data pusher: pushes data to a FTP server. Data is stored on a robust solid state hard disk designed to eliminate the risk of data loss

WinAQMS allows remote access to all of the gas instruments connected to the chamber system and is facilitated via radio, mobile or land line modem as well as wireless network or Ethernet TCP/IP.
When connected to the WinAQMS server the settings and parameters can be changed to suit specific experimental requirements. These parameters include changing instrument parameters and settings, viewing and/or collecting data, setting reporting periods, setting alarms, configuring and initiating calibrations. Data is presented in a number of different formats. Data can be instantaneously generated and displayed as it is logged, or historical data logged from a user defined time period. Instantaneous data or historical data can be displayed as a line graph with multiple parameters plotted in different color lines. When viewing data, the graph updates every minute (or the minimum reporting period set). The graph displays up to three hours of data and shows an auto scale axis and data points. Data can also be displayed in multiple data tables allowing up to 100 parameters to be displayed at once. The parameter displayed can be selected with drop down menus.

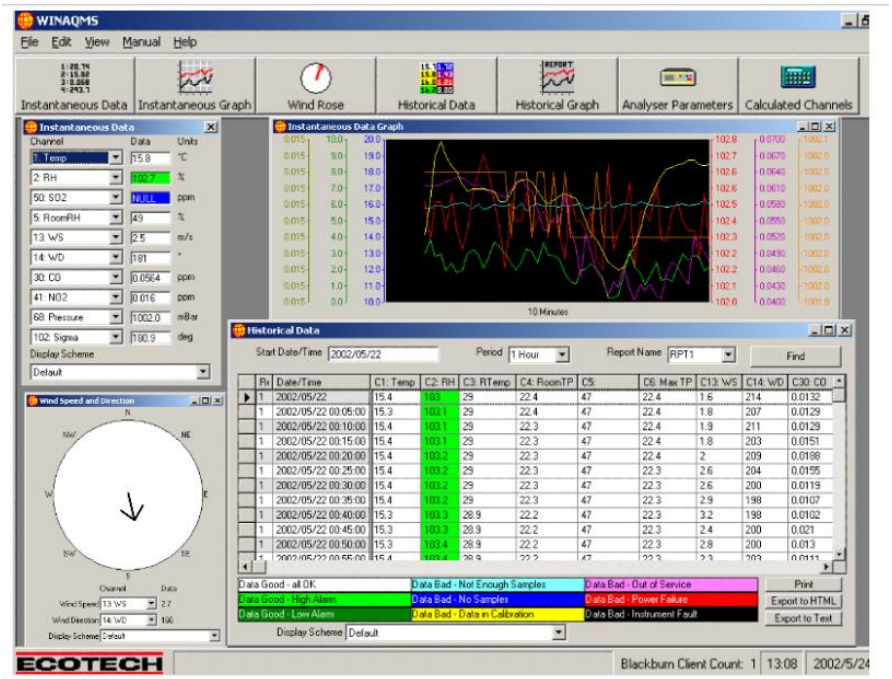



**Figure 8.** WinAQMS software interface

2.7. Sensors communication with chamber system software

There are various ways (i.e. Serial, USB, Ethernet, Bluetooth, GSM cell, and WiFi) a gas or particle sensor communicates with the chamber computer for data logging. As shown in Figures 9a and b, a Teflon-coated stainless steel plate with communication and power ports can be installed on the Teflon-coated inner chamber base (on the right-hand side of the outer chamber) to connect sensors with a computer and power strips located outside of the chamber. The sensors are tested in triplicate and thus, each plate has a communication port and a power port for each sensor for a total of six ports. When necessary, adapters are used to convert, for example, an RS232 or RS485 cable to either Ethernet or USB.

**Figure 9a-b.** Sensor communication (USB) and power ports "plate" (a) and communication "plate" installed on inner chamber base (b)

## 3. Sensor Evaluation

Under the AQ-SPEC program, SCAQMD staff borrows, leases, purchases, or otherwise acquires a group of three identical sensor devices for each sensor type. The sensor technical specifications are clearly defined with the help of the manufacturer or supplier prior to the beginning of testing (see Appendix). As mentioned earlier, the sensors are first evaluated in the field and operated side-by-side with U.S. EPA approved FRM or FEM instruments, which are routinely used to measure ambient concentrations of gaseous or particle pollutants for regulatory purposes. The testing is conducted at one of SCAQMD's existing air monitoring stations (i.e. the Riverside-Rubidoux (RIVR) station in Riverside, CA). Sensors that have demonstrated an acceptable performance in the field are subsequently brought back to the laboratory for additional testing under controlled conditions.

### 3.1 Laboratory evaluation parameters

The laboratory evaluation of the sensors is based on a side-by-side comparison between the sensor device being tested and the FRM/FEM instrument(s) measuring the same pollutant(s). A series of performance-related parameters which would affect actual air quality measurements in the field are tested with a series of carefully designed laboratory chamber experiments similar to those conducted by other organizations (Williams et al., 2014; Spinelle et al., 2013). These parameters include:

- Intra-model variability
- Accuracy
- Precision
- Detection limit
- Linear correlation coefficient ($R^2$)
- Interferents
- Climate susceptibility
- Data recovery
- Sensor decay and degradation
- Baseline drift
- Response to loss of power

Detailed experimental procedures for sensor testing are described in section 3.2. In general, an experiment consists of two stages, a concentration ramping stage where the pollutant level increases, and a steady-state stage where the pollutant concentration remains stable. Most of the parameters, except for the linear correlation coefficient, are evaluated based on data acquired from the steady-state stage.

### 3.1.1. Intra-model variability

Intra-model variability is related to how close the measurements from three units of the same sensor type are to each other. It is evaluated through a set of descriptive statistical parameters, such as mean, median, and standard deviation (, each calculated at low, medium, and high pollutant concentrations. For both aerosol and gaseous experiments, the 1-min average data from each period of a steady-state pollutant concentration in the chamber (usually the last 20 minutes from set of conditions) is considered for this analysis. For a set of three sensors the intra-model variability is reported as a percentage and calculated as follows:

$$\text{Intra-model variability (\%)} = \frac{\text{Mean}_{\text{highest}} - \text{Mean}_{\text{lowest}}}{\text{Mean}_{\text{average}}} * 100 \qquad (1)$$

where,
$\text{Mean}_{\text{highest}}$ is the highest of the three sensors' average concentrations
$\text{Mean}_{\text{lowest}}$ is the lowest of the three sensors' average concentrations
$\text{Mean}_{\text{average}}$ is the average of the three sensors' average concentrations

If the intra-model variability is lower than 20% (both at the concentrations close to the lower detection limit and throughout the full test range), measurements from the three sensors are averaged and used to calculate all other evaluation parameters mentioned in section 3.1. Else, if sensor measurements vary significantly from each other (i.e. intra-model variability larger than 20%) sensor concentrations are treated separately towards the estimation of those evaluation parameters. Bar charts are then created to present the results (Figure 10).

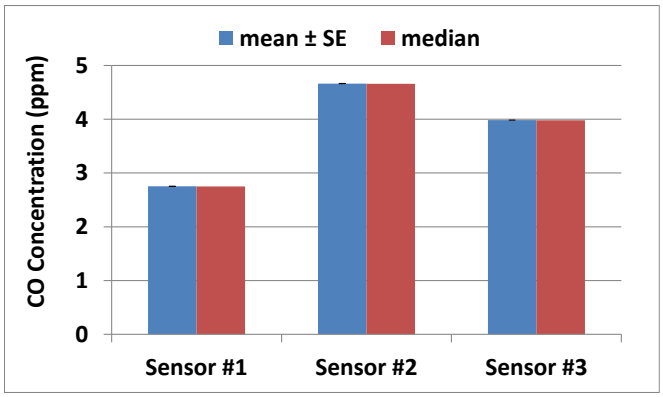



**Figure 10.** An example of the intra-model variability for three carbon monoxide sensors

### 3.1.2. Accuracy

Accuracy is the degree of closeness between the sensors' measured values and the reference value. For the purpose of these chamber tests, accuracy is derived from a concentration ramping experiment at 20 °C and 40% RH. At each pollutant concentration, the difference between the average of the three sensors and the reference instrument is calculated. In this context, accuracy is defined as follows:

$$\mathrm{A}\ (\%) = 100 - \frac{|\overline{\mathrm{X}} - \overline{\mathrm{R}}|}{\overline{\mathrm{R}}} * 100 \qquad (2)$$

where,
$\overline{\mathrm{X}}$ is the average concentration measured by the three sensors throughout the steady-state period considered
$\overline{\mathrm{R}}$ is the reference instrument average concentration during the same steady-state period

It is worth mentioning that accuracy may vary across the same type of sensors at different pollutant concentrations. For simplicity, accuracy is summarized in a table with information acquired at each steady-state condition during a concentration ramping experiment from very low to very high pollutant levels. The higher the positive value (percentage), the higher the sensor's accuracy. For example, a value of 100% implies that sensors measure exactly what the FEM/FRM instrument measures. In cases where sensors overestimate the FEM/FRM instruments by more than 100%, sensor accuracy is reported as a negative value (as shown in Table 1), using equation (2).

**Table 2.** An example of accuracy table

| Steady-state (#) | Sensor mean (µg/m³) | FEM (µg/m³) | Accuracy (%) |
|---|---|---|---|
| 1 | 21.2 | 8.6 | -47 |
| 2 | 49.9 | 19.8 | -52 |
| 3 | 91.8 | 37.8 | -43 |
| 4 | 374.5 | 138.1 | -71 |
| 5 | 776.2 | 245.6 | -116 |
| 6 | 934.7 | 287.8 | -125 |

### 3.1.3. Precision

Precision represents the variation around the mean of repeated measurements of the same pollutant concentration under identical or similar experimental conditions. The more frequently data are collected over a given period of time, the more confidence one has in the reported concentration. For the purposes of this analysis, the sensor's precision (3) is expressed as follows.

$$\mathrm{P}\ (\%) = 100 - \frac{\overline{\mathrm{SE}_{\mathrm{sensor}}}}{\overline{\mathrm{X}}} * 100 \qquad (3)$$

where,

$\overline{\mathrm{SE}_{\mathrm{sensor}}}$ is the standard error of the averaged concentrations of the three sensors during the steady-state period considered
$\overline{\mathrm{X}}$ is the average concentration measured by the three sensors throughout the same steady-state period

Standard error is calculated as:

$$\mathrm{SE}_{\mathrm{sensor}} = \frac{\sqrt{\Sigma\ (\mathrm{X}-\overline{\mathrm{X}})^2}}{\mathrm{n}} \qquad (4)$$

where,

X is the average value of the three sensors concentrations at different times during the steady-state period considered
$\overline{\mathrm{X}}$ is the average concentration measured by the three sensors throughout the same steady-state period

n is the number of measurements taken

During a gas sensor testing experiment, the steady-state time period is on average 20 minutes and since 1-min measurements are collected, 20 steady-state measurement data points are used for this analysis. For consistency, PM sensors are also evaluated using 20 measurements data for precision, although the steady-state period for PM evaluation usually lasts longer than 20 minutes.

Precision may be affected by the environmental conditions chosen. Therefore, this parameter is calculated for each combination of pollutant concentration, T, and RH in climate susceptibility experiments, and presented in a summary table. The higher the percentage value, the higher the sensor's precision.

### 3.1.4. Detection limit

Detection limit, or limit of detection (LOD), is the lowest quantity of a certain pollutant that can be distinguished by a sensor from the absence of that pollutant within a stated confidence limit. For the purpose of this report, the LOD of a sensor is estimated as follows:

$$\mathrm{LOD} = 3.3\sigma/\mathrm{S} \qquad (5)$$

where,
σ is the residual standard deviation of the linear regression line between the average sensor measurements and the corresponding FRM/FEM instrument data. In an excel spreadsheet, σ is also known as the standard error of the predicted reference instrument value for each sensor's value in the linear regression, and is calculated by equation (6).

$$\sigma = \sqrt{\frac{1}{n-2}\left[\sum(R-\overline{R})^2 - \frac{[\sum(X-\overline{X})(R-\overline{R})]^2}{\sum(X-\overline{X})^2}\right]} \qquad (6)$$

where,
X is the average value of the three sensors concentrations at different times during the steady-state period considered
$\overline{X}$ is the average concentration measured by the three sensors throughout the same steady-state period

R is the reference instrument concentration at different times during the steady-state period considered
$\overline{R}$ is the reference instrument average concentration throughout the same steady-state period

n is the number of measurements taken
S is the slope of the linear regression line

### 3.1.5. Linear correlation coefficient ($R^2$)

This parameter expresses the strength of the linear relationship between the average measurements from the three sensor tested and the corresponding reference instrument values. The paired data set acquired from the concentration ramping experiment at 20 °C and 40% RH is entered in an excel spreadsheet and a best-fitting regression curve is calculated along with the corresponding correlation coefficient ($R^2$), slope, and intercept values. An $R^2$ approaching the value of 1 reflects a near perfect agreement between the sensors and FRM/FEM readings, whereas a value of 0 indicates a complete lack of correlation.

### 3.1.6. Interferents

Interferents are factors affecting the sensor's ability to correctly measure the variable(s) of interest (e.g. pollutant concentration, T, RH, etc.). The presence of interferents typically results in inaccurate and/or imprecise measurements. Common interferents include:

- other gaseous and particulate components other than the species of interest
- fluctuation in temperature and relative humidity
- radio frequencies
- power fluctuations
- other contaminants

Gas sensors normally suffer from cross-sensitivity (either positive or negative) to other gaseous species (see Appendix - Table A2). The concentration of the test gas and gaseous interferents is measured using FRM/FEM instruments which typically have an uncertainty of less than 5%.

In the laboratory, the effect of gaseous interferents is evaluated by exposing a sensor to a concentration of the pure interferent. If sensors respond to the interferent, they are subsequently treated under both a known concentration of its target pollutant and also to increasing concentrations of the know interferent.

If that sensors' response correlates with the introduced interferent's concentration, a quantitative relationship is derived and presented. The effect of interferents resulting from fluctuations in environmental conditions (T and RH) are presented in the following section.

### 3.1.7. Climate susceptibility

It is a measure of a sensor's ability to endure variations in environmental conditions, including changes in temperature and relative humidity. A sensor is most useful if it can operate reliably in many different environments. In the laboratory, air quality sensors are tested under a wide range of temperature and relative humidity conditions. For each T and RH combination considered, the sensors' precision is calculated (see Table 2 below).

**Table 3.** Combinations of weather conditions used for climate susceptibility evaluation

| Temp/RH | **Low (15%)** | **Medium (40%)** | **High (65%)** |
|---|---|---|---|
| **Low (5 °C)** | 5 °C, 15% | 5 °C, 40% | 5 °C, 65% |
| **Medium (20 °C)** | 20 °C, 15% | 20 °C, 40% | 20 °C, 65% |
| **High (35 °C)** | 35 °C, 15% | 35 °C, 40% | 35 °C, 65% |

### 3.1.8. Data recovery

Data recovery is calculated using a percentage ratio of the number of valid sensor data points over the total number of data points collected during the testing period (e.g. 10 hours of testing at 1-min time resolution results in up to 600 data points in total). Completeness is an important factor for producing reliable and representative data, as is indicated in the EPA guidelines for regulatory data collection.

$$\text{Data recovery } (\%) = \frac{\mathrm{N}_{\text{valid data}}}{\mathrm{N}_{\text{test period}}} * 100 \qquad (7)$$

where,
$\mathrm{N}_{\text{valid data}}$ is the number of valid sensor data points during the testing period
$\mathrm{N}_{\text{test period}}$ is the total number of data points for the testing period (from start to end)

**Below are other parameters that may have an effect on sensor performance. These will only discussed qualitatively:**

### 3.1.9. Sensor decay and degradation

These terms refer to a progressive decline in sensor performance due to a number of factors. In general, sensor decay/degradation indicates that the sensor loses its ability to collect meaningful measurements over time. Some chemical compounds in the atmosphere can react with and damage sensors in a non-reversible way, limiting their ability to respond reliably to the pollutant(s) of interest. Some sensors (e.g. metal-oxide, electrochemical) should be used within the time frame defined by the manufacturer, even if they are never used in the field and are kept in their original packaging.

### 3.1.10. Baseline drift

It is a gradual change in sensor response to a constant set of environmental conditions (e.g., a standard concentration or zero air) over a certain period of time, during which the true value of the variable measured does not change. It may occur due to a variety of reasons such as changes in weather conditions, sensor "poisoning", and malfunctioning mechanical parts or, in the case of particle (optical) sensors, temporal variations in the intensity of the light source. In the laboratory, sensor's baseline drift is checked at the beginning of an experiment by exposing the sensor to a zero-air chamber environment. When a drift is identified, AQ-SPEC consults with the sensor manufacturer/developer. In such case, units are either sent back to or are remotely calibrated by the manufacturer. If such service is not available, the average drift value is accounted for in the actual sensor readings and is explicitly noted in the laboratory evaluation report.

#### 3.1.11. Response to loss of power

It is the amount of time that a sensor requires to warm up and resume operation after a shutdown cause by a power loss. If a sensor requires a large amount of time to resume operation data continuity and completeness can be significantly affected.

## 3.2. Laboratory testing procedures

### 3.2.1. PM sensor laboratory testing procedure

#### 3.2.1.1. Outer chamber and PM sensors preparation

The equipment used to conduct the PM sensor performance evaluation testing in the laboratory consists of the outer chamber, the PALAS and/or TOPAS particle generators and the particle FEM and/or BAT instruments.

Before the start of an experiment, the chamber wall surfaces are wiped off with kimwipes damped in isopropyl alcohol. Prior to installing the sensor triplicate inside the outer chamber, these undergo routine maintenance according to the manufacturer's user/operation manual. Maintenance procedures include but are not limited to filter replacement, zero calibration, flow rate checks, date/time synchronization, and battery change.

Three units of the same sensor model are installed on individual Teflon trays mounted on the inner chamber base (Figure 3). Sensors inlets are facing towards the middle of the chamber and are a few inches away from where the FEM/BAT aerosol instrumentation sampling inlets are located. Thus, sensors and aerosol instruments sample from the same location inside the chamber. If the PM sensors carry their own batteries, these are fully charged to last for the entire duration of the experiment. If the PM sensors are powered via a power cable then all necessary power connections are made prior to the beginning of testing. Sensors are then switched on before data logging begins. Data is logged in two different ways: internally (saved in the sensor memory) and downloaded offline after the end of an experiment, and/or through a sensor specific software that runs in real-time during an experiment. In the latter case, data can be downloaded either during or after the end of an experiment. A computer cable connects the sensors from inside the chamber to an external computer.

Subsequently, the chamber door is closed, the system is powered on and the chamber is flushed with dry, particle- and gas-free air. Particle mass and number concentrations are measured through the FEM GRIMM reference monitor until negligible PM levels (e.g. below 0.5 $\mu g/m^3$) are recorded. The target

chamber temperature and relative humidity levels are pre-set through the computer software. When the chamber environmental conditioning commences, baseline measurements of chamber PM, as well as temperature and relative humidity values, are recorded for 5 minutes prior to beginning aerosol injection inside the chamber. When the chamber temperature and relative humidity reach the target set-points, dry aerosol is injected into the chamber at a known concentration and size range.

3.2.1.2. Aerosol atmosphere and testing

In a typical experiment, depending upon the desired particle size range, either the large particle or the ultrafine/fine particle generator is used to produce test particles inside the chamber. The frequency and duration of aerosol injection are controlled by an integrated software specifically designed to operate the particle generators and the chamber environmental conditions. Due to the relatively large volume of the outer chamber and the low flow rate of the dry aerosol produced by the particle generator it takes between 2-3 hours to reach a stable aerosol concentration in the outer chamber. Every concentration step change occurs only after a stable aerosol concentration has been reached in the outer chamber and a sufficient number of sensor measurements has been taken.

The standard procedure of a PM sensor evaluation in the laboratory chamber consists of two experimental phases:

<u>Phase 1</u>: Concentration ramping

Once the chamber has reached the desired average ambient conditions of 20 °C and 40%, a concentration ramping experiment begins. A total of 6 concentration steps are selected to simulate a diverse pollutant profile from very low (0-10 µg/m$^3$) to very high (~300 µg/m$^3$) (as shown in Figure 11). Experimental parameters, such as aerosol injection frequency and duration, are pre-determined and programmed in a sequence. The fans that are used to create uniform mixing inside the chamber are held at constant speed (e.g. frequency of 25 Hz) across all testing conditions to eliminate variations in the particle size distribution.

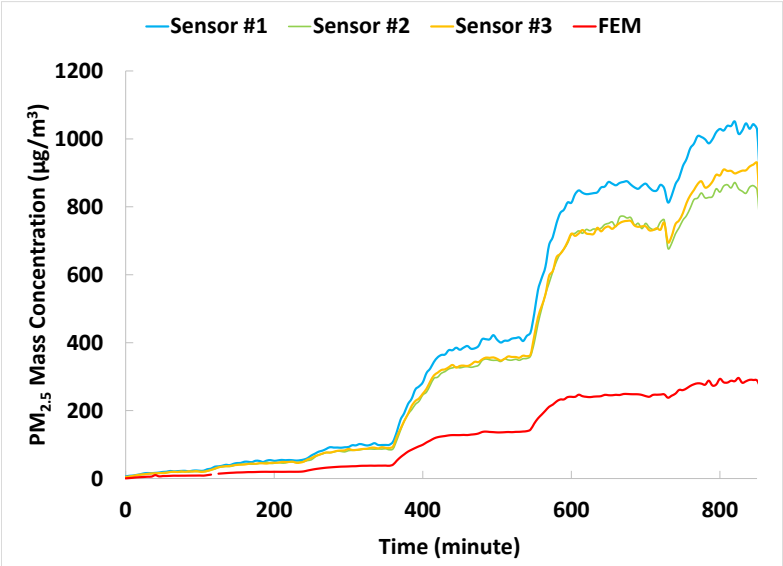



**Figure 11.** An example of an aerosol Phase 1 experiment

Phase 2: Effect of T and RH

Aerosol concentration, temperature and relative humidity are each varied at three different levels (i.e., low, medium and high) for a total of 27 different sets of combinations (same as in Table 2 but at three different pollutant concentrations). Specifically, aerosol concentration is varied between low (10-15 µg/m$^3$), medium (50-60 µg/m$^3$) and high (120-150 µg/m$^3$). Temperature is varied between low (5 °C), medium (20 °C) and high (35 °C). Relative humidity is varied between low (15%), medium (40%) and high (65%).

It should be noted that a low relative humidity of 15% cannot be achieved inside the chamber at 5 °C, without purging dry zero-air inside the chamber. However, purge air cannot be used during an aerosol test because this would continuously dilute the aerosol concentration, which is inappropriate for sensors laboratory characterization. In this case, the relative humidity is maintained at levels as low as 20-25%.

After all particle testing experiments have been completed, the liquid salt solution in the glass bottle is replaced with de-ionized water that flushes the aerosol generation system lines for about 20 min to remove any accumulated salt. Likewise, the large solid particle powder is also wiped off from the surfaces of the generator and the wall surfaces of the outer chamber are cleaned with isopropanol and the system is set to be flushed with zero-air for several hours.

### 3.2.2. Gaseous sensor laboratory testing procedure

#### 3.2.2.1. Inner chamber and gaseous sensors preparation

Gaseous sensors measuring criteria and non-criteria pollutants, including CO, $NO_x$, $O_3$, $SO_2$, and $H_2S$ are evaluated in the cylindrical-shaped Teflon-coated inner chamber (Figure 5). Before the start of an experiment, the inner chamber wall surfaces are wiped off with kimwipes damped in isopropyl alcohol. Prior to their installation inside the laboratory chamber, the gaseous sensors have undergone routine maintenance according to the manufacturer's user manual. Maintenance procedures include but are not limited to filter replacement, zero calibration, flow rate checks, date/time synchronization, and battery change.

Three identical gaseous sensors (i.e, same make and model) are installed on individual Teflon trays mounted on the inner chamber base (Figure 3). Sensors inlets are facing towards the middle of the chamber and are within a few inches away from where the FRM/BAT instrumentation's sampling manifold inlet is located. Thus, sensors and gas instruments sample from the same location inside the chamber. If the gaseous sensors carry their own batteries, those are fully charged to last for the duration of the experiment. If the gaseous sensors are powered via a power cable then all necessary power connections are made. Sensors are switched on before data logging begins. Data is logged in two different ways: internally (saved in sensor memory) and downloaded offline after the end of an experiment, and/or through a sensor specific software that runs in real-time during an experiment. In the latter case, data can be downloaded either during or after the end of an experiment. A computer cable connects the sensors from inside the chamber to an external computer.

Subsequently, the chamber door is closed, the system is powered on and the chamber is flushed with dry, particle- and gas-free air. Gas concentrations are measured by reference instruments and monitored through the WinAQMS software until the gas concentration stops decreasing and reaches the baseline value for the experiment. In Mode B, the T and RH can be pre-set on the computer software. When the

chamber target environmental conditions are achieved, baseline measurements of inner chamber gaseous concentration, temperature and relative humidity are recorded for at least 5 min prior to the introduction of a target gas from a certified compressed gas cylinder.

3.2.2.2. Gaseous atmosphere and testing

The standard procedure of a gaseous sensor evaluation test in the laboratory chamber consists of three experimental phases:

Phase 1: Concentration ramping (Mode A)

The concentration range tested varies from very low to very high for a specific gas. Dynamic gas dilution is performed by the dilution calibrator. Gas (e.g. CO, $NO_x$, $SO_2$) from a certified compressed gas cylinder (or generated by the T700U calibrator in case of $O_3$) is introduced into the calibrator where it is diluted with unconditioned zero-air. Subsequently, the zero-air diluted gas is introduced into the inner chamber at the desired concentration. This is a simple control system where a small amount of gas and a short stabilization period is needed (approximately 40 min for each concentration step) (Figure 12).

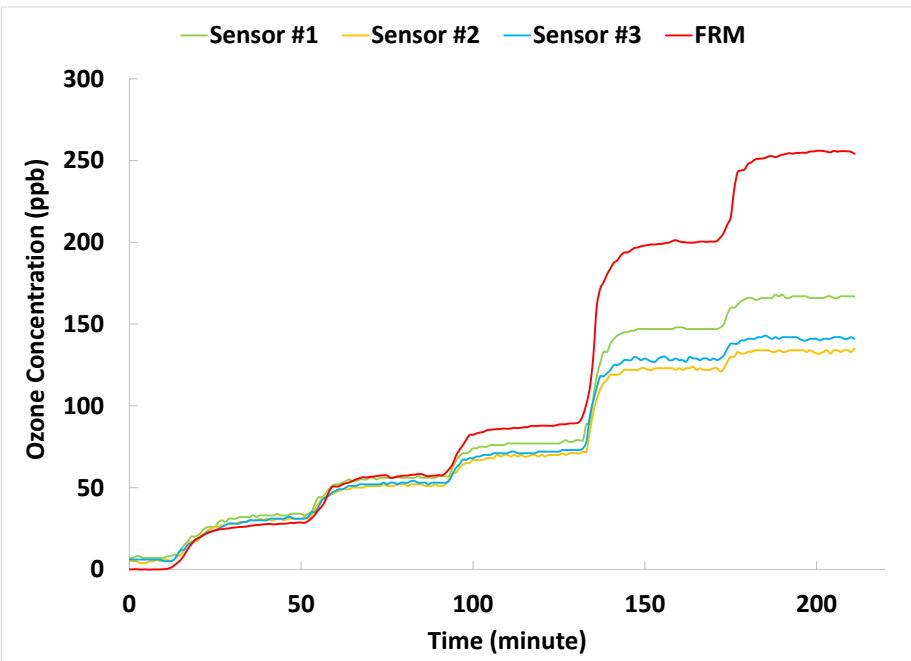



**Figure 12.** An example of a gas Phase 1 and 2 experiment

Phase 2: Effect of T and RH (Mode B)

The temperature and relative humidity parameters are each varied at low, medium and high level for a total of 9 different sets of combinations. Temperature is varied between low (5 °C), medium (20 °C) and high (35 °C). Relative humidity is varied between low (15%), medium (40%) and high (65%) (see Table 2)

Similar to the Phase 1 experiment, target gas concentration ramping from very low to very high is conducted for each combination of environmental conditions. Within a ramping experiment, each set-

point is maintained for 40 minutes until a stable gas concentration is reached in the inner chamber as recorded by the reference instrument.

Correlation coefficients ($R^2$) for these 9 experiments are derived and compared to each other. A smaller $R^2$ value indicates that the sensor is negatively influenced by the corresponding T and RH conditions.

Phase 3: Effect of interferent gases (Mode B)

In the laboratory, the effect of interferents resulted from other gaseous components is evaluated by exposing a sensor to a target concentration of pure interferent. Depending on a sensor's target pollutant type and its detecting technology, the interferents and their concentrations are chosen as recommended by 40 CFR Part 53 Table B-3 (See Appendix Table A2) or from information provided in previous studies reported in the literature. For example, for an electrochemical ozone sensor, 0.5 ppm $NO_2$ and 0.5 ppm $SO_2$ is introduced in the chamber, and the sensor's response is evaluated. If sensors respond to the interferent, they are subsequently treated with a mixture of a known concentration of the target pollutant and various concentrations (in a concentration ramping mode) of the identified interferent. When sensors' response correlates with the introduced interferent's concentration, a quantitative relationship is derived and presented.

### 3.3. Data analysis

Reference instruments and sensor data are first validated following basic QA/QC procedures (i.e., obvious outliers, negative values and invalid data points are eliminated from the data-set). Valid data is averaged over 1- and 5-min intervals, and data from the sensors and the reference instrument(s) is matched by date/time. Statistical analysis is then conducted to quantitatively evaluate the parameters as described in sections 3.1.1. – 3.1.8.

## 4. Study limitations

This environmental chamber system is the first of its kind for the purpose of evaluating low-cost air quality sensors. Despite of its capability in generating stable and reproducible various gas and particle test atmospheres under normal and extreme temperature and relative humidity conditions, some study limitations need to be recognized.

To evaluate sensor's climate susceptibility, 9 representative weather (T and RH) combinations are chosen based on our objective judgement. Although the chamber has the potential to generate even lower or higher T and RH, due to the tight testing schedule, we could not afford to exhaust testing of more weather combinations. As suggested in previous studies (Sohn et al., 2008; Wang et al., 2010, 2015) sensor failures were observed at low temperature such as 0 °C and high RH of 95%. Considering the low possibility of a consumer encountering such weather combinations, we decided to not include those conditions.

The effect of shock changes in T and RH on sensor's performance is also of interest. Due to the tight testing schedule, our experimental design only presents results under shock increase in RH when RH set-points increased from 15% to 40%, and then from 40% to 65%. Other experiments intended to test sensors' climate susceptibility are mostly conducted at stable T and RH. The only exception is at 5 °C, where the observed actual RH is varied around the set-points through humidification and dehumidification cycles.

In this study, sensor's response time is not tested because of chamber system design. After the sensor triplicate is installed on the sensor trays inside the chamber, the chamber door is closed. Pollutant concentration is gradually increased over 30 minutes (gas) or 90 minutes (aerosol) to the set-points. Therefore, it is not possible to calculate response time. So far, our observations indicate that the greatest majority of the sensors have response times very similar to their measurement intervals.

With respect to the artificial aerosol generation/dust powder dispenser systems, it is possible to approximate a broad range of pm mass concentrations as well as the bimodal size distribution of the urban ambient air. However, the chemical nature, the pre-defined size distribution, and physical properties of the generated artificial aerosol and the Arizona road dust type dust powder cannot replicate the diverse profile of an urban ambient aerosol chemical composition.

Last but not the least, sensors might have experienced some small alterations after their first two-month deployment in the field. At the beginning of the laboratory evaluation, sensors are subjected to a concentration ramping experiment to determine what their condition is relative to their field deployment. If significant changes are observed, AQ-SPEC contacts the sensor manufacturer/developer and action is taken that may involve calibration, maintenance, servicing. . Despite this limitation, AQ-SPEC is currently tests off-the-shelf devices. To the best of our judgement, testing a sensor an off-the-shelf unit first in the field under ambient conditions and subsequently in the laboratory chamber under "extreme" weather conditions is the preferred approach.

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## Appendix

### Reference methods

Federal Reference Method (FRM): A FRM is an "EPA approved" method, sampler or analyzer that utilizes the measurement principles and calibration procedures specified in the Code of Federal Regulations (40 CFR Part 50).

Federal Equivalent Method (FEM): A FEM is an ambient air monitoring method that has been designated by EPA as an equivalent method under 40 CFR Part 53.

To be considered as a viable FRM/FEM candidate, a potential measurement technique must:

- Provide accurate and reliable measurements
- Be relatively free of significant interference from gases or other agents that may occur in ambient air
- Provide continuous or nearly continuous measurements in near real-time
- Be commercially available at modest or reasonable cost
- Be reasonably easy and convenient to operate by typical air monitoring personnel to produce measurements of good accuracy and precision
- Be reasonably and routinely field-deployable for use as a quality assurance reference in monitoring networks

**Table A1. List of sensors currently available for field and laboratory evaluation within the AQ-SPEC program (updated on 08/01/16)**

| Sensor | Compound(s) Measured |
|---|---|
| AeroQual Ozone 500 | $O_3$ |
| RTI MicroPEM | $PM_{2.5}$ (real-time & integrated) |
| Shinyei PM Sensor | $PM_{2.5}$ |
| MetOne Community Monitor | PM |
| MetOne E-Sampler | PM |
| AQMD E-Box (Dylos, Yoctopuce Met, Valarm) | Particle Count, T, RH, BP |
| Speck (CMU) Airviz, Inc, Version 1 | $PM_{2.5}$ |
| AirBeam PM monitor | $PM_{2.5}$ |
| Sensaris Eco PM | $PM_{2.5}$ and VOC, T, RH |
| Air Quality Egg | PM, CO, $NO_2$ |
| SDL307 mini laser | $PM_{10}$, $PM_{2.5}$ |
| Alphasense B4 $NO_2$ (Alphasense ISB) | $NO_2$ |
| Alphasense B4 $NO_2$ with E-chem 328 board | $NO_2$ |
| Alphasense B4 Ozone (Alphasense ISB) | $O_3$ |
| Alphasense B4 Ozone with E-chem 328 board | $O_3$ |
| AQ Mesh (V3.0) | NO, $NO_2$ and $O_3$, CO, and $SO_2$ |
| AQ Mesh (V4.0) | NO, $NO_2$ and $O_3$, CO, and $SO_2$ |
| Unitec Sense-it | CO, $NO_2$, $O_3$ |
| Alphasense PM | PM fractions |

| | |
|---|---|
| ELM (1st deployment) | Multi-gas (non-VOC) and PM |
| 2B POM | $O_3$ |
| Partector | LDSA (PM) |
| TSI AirAssure | $PM_{2.5}$ |
| Landtec AQ Mesh (V1) | NO, $NO_2$ and $O_3$, CO, and $SO_2$ |
| Dylos DC1100/DC1700 | Particle Count |
| Smart Citizen | NO, $NO_2$, CO, RH, T |
| Spec Sensors w/ Intel Edison | $O_3$, $NO_2$, $SO_2$, CO |
| Air Quality Egg V2 $O_3$/$SO_2$ | $O_3$ and $SO_2$ |
| Air Quality Egg V2 CO/$NO_2$ | CO and $NO_2$ |
| Libelium | Multi-gas (VOC) and PM |
| Yoctopuce VOC | VOC |
| ELM (2nd deployment) | Multi-gas (VOC) and PM |
| 3M AQM | PM, $NO_2$, NO, VOC |
| Awair | T, RH, $CO_2$, VOC, dust |
| Cube | T, RH, $CO_2$, VOC |
| Yoctopuse VOC w/Valarm | VOC |
| Alphasense B4 | O3, CO, $CO_2$, $H_2S$, $SO_2$, NO, $NO_2$, VOC |
| AQMD Pilot Study | PM |

**Table A2.** Gas Interferent Concentration (ppm) from 40 CFR Part 53 Table B-3

| Pollutant | Analyzer type | $H_2S$ | $SO_2$ | $NO_2$ | NO | $CO_2$ | $O_3$ | Water vapor | CO |
|---|---|---|---|---|---|---|---|---|---|
| $SO_2$ | Ultraviolet Fluorescent | 0.1 | [3]0.14 | 0.5 | 0.5 | | 0.5 | 20,000 | |
| $SO_2$ | Flame Photometric | 0.01 | [3]0.14 | | | 750 | | [2]20,000 | 50 |
| $SO_2$ | Gas Chromatography | 0.1 | [3]0.14 | | | 750 | | [2]20,000 | 50 |
| $SO_2$ | Electrochemical | 0.1 | [3]0.14 | 0.5 | 0.5 | | 0.5 | [2]20,000 | |
| $SO_2$ | Conductivity | | [3]0.14 | 0.5 | | 750 | | | |
| $O_3$ | Chemiluminescent | [2]0.1 | | | | 750 | [3]0.08 | [2]20,000 | |
| $O_3$ | Electrochemical | | 0.5 | 0.5 | | | [3]0.08 | | |
| CO | Non-dispersive Infrared | | | | | 750 | | 20,000 | [3]10 |
| CO | Electrochemical | | | | 0.5 | | | 20,000 | [3]10 |
| CO | IR Fluorescent | | | | | 750 | | 20,000 | [3]10 |
| $NO_2$ | Chemiluminescent | | 0.5 | [3]0.1 | 0.5 | | | 20,000 | |
| $NO_2$ | Electrochemical | | 0.5 | [3]0.1 | 0.5 | 750 | 0.5 | 20,000 | 50 |

[1]Concentrations of interferent listed must be prepared and controlled to ±10% of the stated value
[2]Do not mix with the pollutant.
[3]Concentration of pollutant used for test. These pollutant concentrations must be prepared to ±10% of the stated value.

**Table A3.** A documented sequence for a typical aerosol concentration ramping experiment

| Seq # | SeqTime | Temp | RH | PreInj | Inj | PostInj | Off | CycInj | TCT | TFT | CalSeq | Purge |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 150 | 20 | 40 | 1 | 1 | 1 | 32 | 8 | | | | OFF |
| 1 | 150 | 20 | 40 | 1 | 1 | 1 | 32 | 4 | | | | OFF |
| 2 | 150 | 20 | 40 | 1 | 1 | 1 | 32 | 2 | | | | OFF |
| 3 | 150 | 20 | 40 | 1 | 1 | 1 | 32 | 0 | | | | OFF |
| 4 | 150 | 20 | 40 | 1 | 3 | 1 | 32 | 0 | | | | OFF |
| 5 | 150 | 20 | 40 | 1 | 4 | 1 | 32 | 0 | | | | OFF |
| 6 | 90 | 20 | 40 | | | | | | | | | ON |
| STOP | | | | | | | | | | | | |

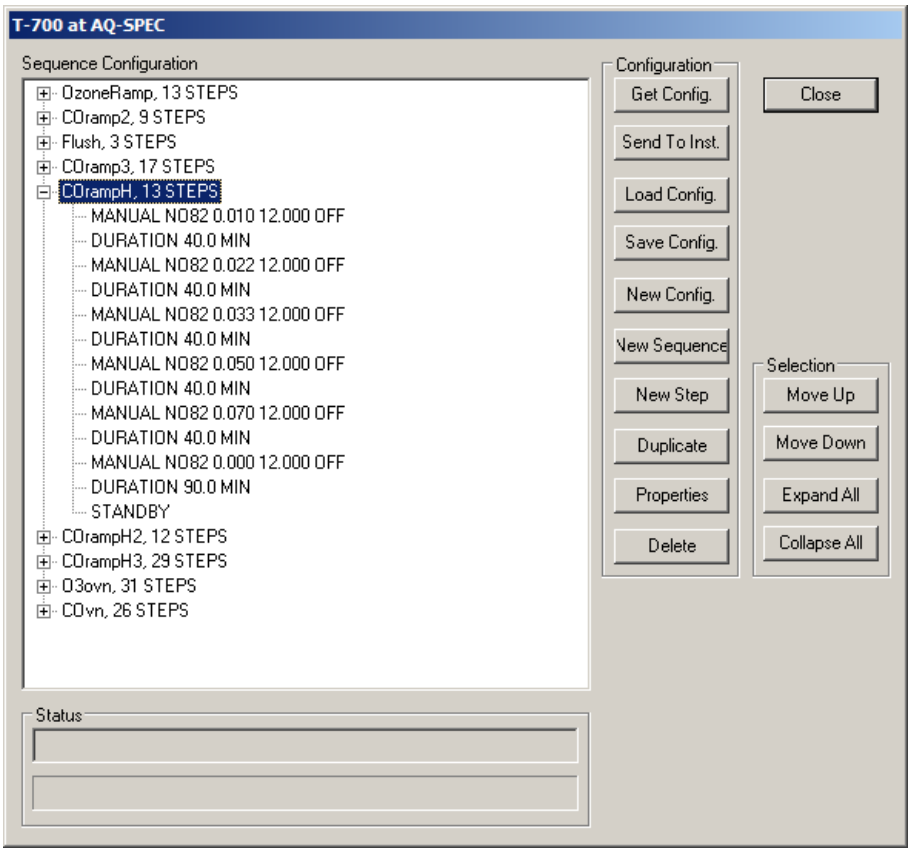


**Figure A1.** A documented sequence for a typical ozone concentration ramping experiment

**Chamber system maintenance**

To ensure optimal performance of the chamber system, a series of operation and maintenance efforts are conducted regularly.

**Environmental Chamber:**

1. Chamber walls are wiped clean with isopropyl alcohol before the start of an experiment.
2. Ion exchange water filter is replaced as indicated by color change.
3. Aerosol mixing duct is cleaned every 6 months or sooner.
4. Chamber HVAC system is inspected by an external consultant every 12 months.

**Zero-air Generation System:**

5. Catalysts in the Zero-air scrubber are changed every 12 months or sooner if clearly shown by the indicator.

**Aerosol/Gas Generation System:**

6. Dilution calibrator is calibrated every 12 months.
7. PALAS aerosol generator is flushed with deionized water for 20 minutes after a full day of experiment.
8. TOPAS solid aerosol generator is cleaned after each completed sensor testing.

**Reference instrument:**

An analyzer is calibrated (or recalibrated):

- upon initial installation,
- following physical relocation,
- after any repairs or service that might affect its calibration,
- following an interruption in operation of more than a few days,
- upon any indication of analyzer malfunction or change in calibration,
- at some routine interval (see below).

9. FRM gas analyzers are calibrated using certified gas cylinders every 6 months, and span calibrated before the start of testing a new sensor.
10. FEM GRIMM dust monitor is regularly maintained as indicated by the instrument manufacturer. Maintenance includes filter change, tubing flushing with clean air, memory card restoration. GRIMM dust monitor is sent back to the manufacturer for re-calibration every 12 months.