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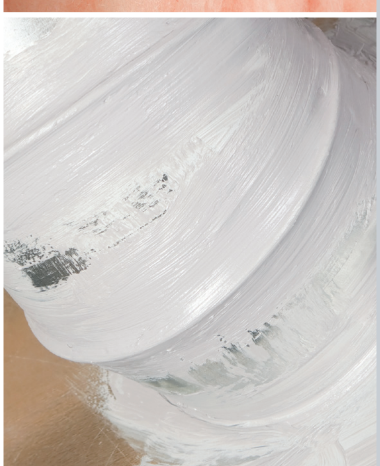

Development of Laboratory Test Methods for Low-Cost Indoor Air Quality Sensors

February 2024

Building America

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Development of Laboratory Test Methods for Low-Cost Indoor Air Quality Sensors

Prepared for:
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FOREWORD

The U.S. Department of Energy (DOE) Building America Program has spurred innovations in building efficiency, durability, and affordability for more than 25 years. Elevating a clean energy economy and skilled workforce, this world-class research program partners with industry to leverage cutting-edge science and deployment opportunities to reduce home energy use and help mitigate climate change.

In cooperation with the Building America Program, Newport Partners is one of many Building America teams working to drive innovations that address the challenges identified in the program's Research-to-Market Plan.

This report, *Development of Laboratory Test Methods for Low-Cost Indoor Air Quality Sensors*, develops two test methods—one for $PM_{2.5}$ sensors and one for CO_2 sensors—and represents a step toward broad market adoption of low-cost indoor air quality sensors.

As the technical monitor of the Building America research, the National Renewable Energy Laboratory encourages feedback and dialogue on the research findings in this report as well as others. Send any comments and questions to building.america@ee.doe.gov.

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- Matt Matheny, Home Ventilating Institute and Healthy Air Research and Certification Authority
- All Members of American Society for Testing and Materials D22.05 Subcommittee.

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LIST OF ACRONYMS

AQMD	Air Quality Management District
AQ-SPEC	Air Quality Sensor Performance Evaluation Center
ASTM	American Society for Testing and Materials
CFR	Code of Federal Regulations
CO_2	carbon dioxide
CO	carbon monoxide
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
FEM	Federal Equivalent Method
FRM	Federal Reference Method
g/cm^3	grams per cubic centimeter
H_2S	hydrogen sulfide
H_2SO_4	sulfuric acid
HARCA	Health Air Research and Certification Authority
HVI	Home Ventilating Institute
IAQ	indoor air quality
ISO	International Organization for Standardization
KCl	potassium chloride
$\mu g/m^3$	micrograms per cubic meter
NaCl	sodium chloride
NO	nitric oxide
NO_x	nitrogen oxides
NO_2	nitrogen dioxide
O_3	ozone
PM	particulate matter
$PM_{2.5}$	particulate matter of 2.5 micrometers in diameter or smaller
PM_{10}	particulate matter of 10 micrometers in diameter or smaller
PPM	parts per million
PSL	polystyrene latex
RSD	relative standard deviation
SBS	Sick Building Syndrome
SO_2	sulfur dioxide
TAG	Technical Advisory Group
tVOC	total volatile organic compound
VOC	volatile organic compound

EXECUTIVE SUMMARY

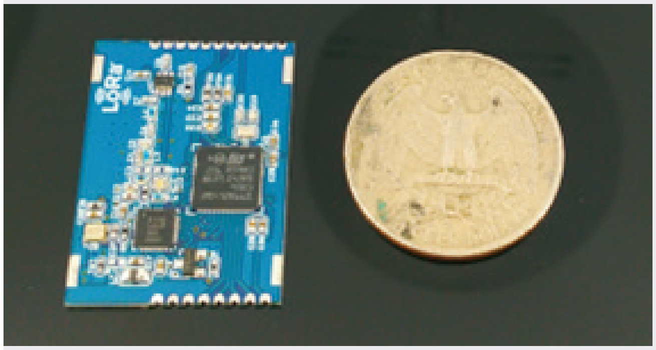
Indoor air quality (IAQ) has become an integral building science component for efficient, airtight homes and buildings. As established in multiple studies, we spend much of our time indoors (Klepeis et al. 2001), making our indoor environment especially important.

Common approaches for providing healthy IAQ are pollutant source control, filtration, and ventilation. However, these approaches could be improved by the addition of a fourth measure—active IAQ monitoring with the use of low-cost IAQ sensors. Using IAQ sensors to monitor indoor conditions can complement other IAQ control measures.

Home occupants alerted to the presence of an indoor air pollutant might boost ventilation, change heating and cooling filters, activate air purifiers, or even leave the space until sensors indicate lower levels of pollutants. Feedback from IAQ monitors could change consumer behavior in myriad ways, such as purchasing products low in volatile organic compounds (VOCs). Controls could automatically control ventilation in a dynamic way that saves energy when indoor air pollutants are not present and increases ventilation rates when needed in response to an indoor pollutant event. In homes, offices, schools, factories, public gathering places, and other locations, the applications for real-time feedback and response to IAQ conditions are numerous and have the potential to improve human health through improved indoor environments.

Problem Statement

While air quality monitors, used for tracking ambient (outdoor) air pollution, have been proven reliable through rigorous requirements and testing protocols established by the U.S. Environmental Protection Agency (EPA), these Federal Reference Method (FRM) and Federal Equivalent Method (FEM) monitors (Code of Federal Regulations 40 Part 53) often cost thousands of dollars, making consumer use or even commercial applications impractical. To be used for most common indoor applications, sensors need to be low-cost enough for everyday use.



Low-cost indoor air quality sensors, including sensor systems with multiple sensors, are widely available on the market, with hundreds of devices for purchase at prices ranging from several dollars to a few hundred dollars. These sensors are intended to detect a variety of indoor air pollutants such as particulate matter (PM), nitrogen dioxide (NO_2), carbon dioxide (CO_2), and VOCs. Some leading innovative residential builders have installed custom sensor arrays in their homes to create dynamic ventilation systems, or to validate their IAQ claims for their buyers. During the COVID-19 pandemic, IAQ sensors received increased attention for their potential to evaluate viral load in a space. A September 2021 New York Times article was one of many during the pandemic that discussed the use of CO_2 sensors to monitor possible viral levels (Parker-Pope 2021).

A primary barrier to using low-cost IAQ sensors to improve air quality, or to provide reliable information on IAQ status in indoor environments, is that there has been no established method for determining how well low-cost sensors work. Manufacturers perform their own testing, but this testing varies across private organizations and does not carry with it the credibility of testing performed to a standard that can be repeated by other organizations and compared to other manufacturer results using the same test method. Without any way of reliably evaluating low-cost sensors, the ability to use them to improve IAQ may be limited. A standardized method of testing allows for the evaluation of sensors and sensor units in a way that is reliable and comparable to other sensors.

Research Questions

- Can proprietary test procedures for evaluating IAQ sensors be transitioned to fully vetted test methods that can be published as consensus test standards?

- Can test methods be published for sensors of one aerosol-type pollutant ($PM_{2.5}$) and one gas-type pollutant (CO_2) that can then be used as models for future test methods for sensors of other aerosol/gas pollutants?

- Can adequate stringency be incorporated into test methods for $PM_{2.5}$ and CO_2 that provide repeatability and reliability while minimizing testing cost and gaining broad consensus buy-in through the American Society for Testing and Materials (ASTM) process?

- Can key criteria for IAQ performance be evaluated, such as correlation using the Pearson linear coefficient of determination, with FEM instruments, accuracy, precision, interference, stability, drift, and response to varying levels of temperature and relative humidity?

Objectives

The objective of this project was to develop laboratory test methods for evaluation of low-cost IAQ sensors and provide technical support to industry stakeholders during the development of an ASTM standard based on these test methods. The desired outcome supports the development of dependable smart ventilation systems that rely on accurate, low-cost IAQ sensors to safeguard occupant health while minimizing energy use.

Methodology

The project team began the process of developing IAQ sensor test methods (summarized in Figure ES-1) using an existing prototype methodology developed by the South Coast Air Quality Management District's (AQMD) laboratory dedicated to sensor testing, the Air Quality Sensor Performance Evaluation Center (AQ-SPEC). AQ-SPEC described the creation of a prototype test chamber, along with test procedures in *Development of an Environmental Chamber for Evaluating the Performance of Low-Cost Air Quality Sensors Under Controlled Conditions* (Papapostolou et al. 2017) and *Laboratory Evaluation of Low-Cost Air Quality Sensors Laboratory Setup and Testing Protocol* (Polidori, Papapostolou, and Zhang 2016), which could be used for evaluating sensors for a variety of pollutants.

Figure ES-1. Overview of project process

To adapt the system developed by AQ-SPEC, the project team gathered stakeholders in a Technical Advisory Group (TAG), meeting 15 times from 2018–2020 to work through multiple drafts. Work focused on adjusting the procedures based on technical expertise and input, and transitioning the language to enforceable and repeatable standard language.

The TAG process was also vital in building interest with organizations most likely to use the final product—laboratories, sensor manufacturers, and manufacturers of other IAQ technologies such as ventilation systems. With several ASTM D22.05 Subcommittee members on the TAG, the group was also able to identify possible barriers to standard adoption early in the process.

The project team focused on two priority pollutants, one particle and one gas. Particles and gases represent two major categories of pollutants encountered in indoor environments. By choosing one of each, it is likely that many of the approaches for each model pollutant will be applicable, or adaptable, for other pollutants in that same class. Therefore, the two priority pollutants will act as models for future test method development. Particulate matter of 2.5 micrometers in diameter or smaller ($PM_{2.5}$), a pollutant with significant negative impacts on human health, was selected for the particle. CO_2 was selected for the gas. After developing complete test method drafts with TAG consensus and approval, the project team conducted laboratory testing following the draft test methods to demonstrate that the test conditions as described were feasible and repeatable.

The TAG approved any final adjustments to the drafts identified during testing before providing consensus approval to introduce the draft to the ASTM D22.05 Subcommittee on Indoor Air. The project team then worked with ASTMD22.05, providing technical support related to standard development and helping to move the standards toward completion and publication.

Summary of Results

The project team was able to develop two test methods—$PM_{2.5}$ sensors and CO_2 sensors—that were technically feasible and resulted in a high level of testing rigor (recognized by members of the ASTM D22.05 Subcommittee). After three ASTM D22.05 Subcommittee ballots and one final joint concurrent ballot between the ASTM D22.05 Subcommittee and the ASTM D22 Committee on Air Quality, the $PM_{2.5}$ sensor test method was approved. ASTM published the approved test method, ASTM D8405-21 *Standard Test Method for Evaluating* $PM_{2.5}$ *Sensors or Sensor Systems Used in Indoor Air Applications*, in September 2021.

The draft CO_2 test method was well-received by the ASTM D22.05 Subcommittee and received more than 90% affirmative ballots during the first subcommittee ballot. As expected, subcommittee members identified multiple items for edit/improvement after the first ballot, and the draft will need at least one more subcommittee ballot before approval. At the time of this report, the CO_2 draft was being prepared for its second ASTM D22.05 Subcommittee Ballot.

Beginning in 2022, the Home Ventilating Institute (HVI) and Health Air Research and Certification Authority (HARCA) are working to develop an industry certification program for IAQ sensors referencing the *ASTM D8405-21* test method.

Conclusions and Significance

With the ability to test low-cost IAQ sensors using a standardized approach, we can evaluate the performance of sensors that could be used as occupant feedback devices, ventilation control devices, filter change notifications, and even alerts when a space has become over-occupied relative to the current ventilation rates. More efficient demand-controlled ventilation that improves IAQ while avoiding over-ventilation is made possible through the integration of reliable IAQ sensors.

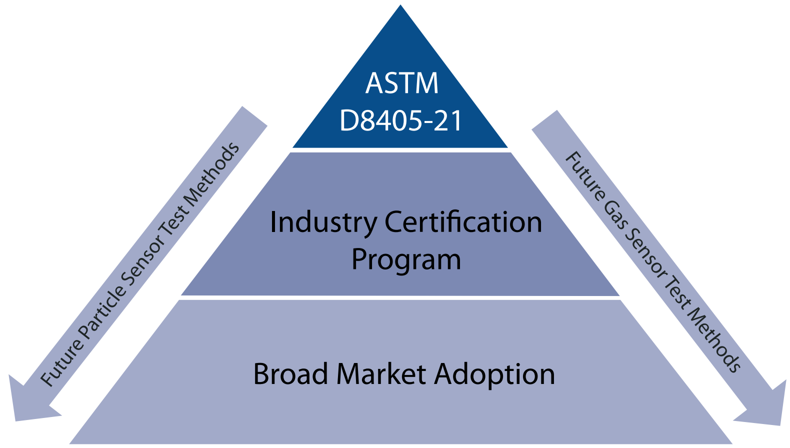


Figure ES-2. Potential impact of project

The publication of the first laboratory test method designed to evaluate IAQ sensors in *ASTM D8405-21* establishes an important example that enables development of further test methods based on this model for pollutants, such as CO_2, particulate matter of other sizes, NO_2, etc. An industry certification program referencing this test method can act as a bridge to consumers, publicizing sensor performance data and allowing IAQ sensor manufacturers to market their products based on certified testing results from an independent third party. This project represents the first step toward integrating an additional, reliable tool for improving and monitoring IAQ—the low-cost IAQ sensor.

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1 Introduction

Along with energy efficiency, durability, and quality construction, indoor air quality (IAQ) is an important consideration for anyone who lives, works, or spends time in a home, office, or other type of structure. As established in multiple studies, we spend much of our time indoors (Klepeis et al. 2001).

Commonly encountered indoor air pollutants can have effects on occupant health that are both acute and chronic. The EPA lists negative health effects of indoor pollutants that range from symptoms such as headaches and throat irritation, to asthma triggers, to long term lung diseases and cancer, as well as heart disease (U.S. EPA 2022a).

These effects can be driven by a variety of indoor pollutants. The Lawrence Berkeley National Laboratory publication *Why We Ventilate* identifies formaldehyde, acrolein, and particulate matter 2.5 micrometers and smaller ($PM_{2.5}$) as the indoor air pollutants of most concern. The paper also discusses many other prevalent indoor pollutants with negative effects on human health, such as nitrogen dioxide (NO_2) and carbon monoxide (CO), among others (Logue et al. 2011). The EPA also lists other indoor pollutants of concern including volatile organic compounds (VOCs), radon, and other pollutants such as mold, bacteria and viruses, pet dander, and pests (U.S. EPA 2022b).

In 2010, the World Health Organization published a guideline for indoor air quality and discussed nine key indoor air pollutants, including "benzene, carbon monoxide, formaldehyde, naphthalene, nitrogen oxide, polycyclic aromatic hydrocarbons … radon, trichloroethylene, and tetrachloroethylene" (World Health Organization 2010). The primary approaches for dealing with indoor pollutants are shown in Figure 1.

While effective at controlling indoor air pollutants and improving indoor environments, source control, ventilation, and filtration may not be the only tools available for addressing IAQ. Source control can limit pollutant exposure but cannot remove all sources of pollutants. For example, cooking will always be an activity that occurs in dwellings and is a source of several indoor pollutants. High-performance filtration can help remove some pollutants, such as particles and airborne viruses, but it is possible that occupants will be exposed to pollutants before filtration has the opportunity for removal.

Ventilation can help improve air quality, but only if fans are activated. Often ventilation systems are not designed to be directly responsive to the presence of pollutant concentrations in a space. Rather, they are designed either to run constantly or on a schedule, which may waste energy by operating when no pollutants are present and will not respond to increased need for ventilation as pollutants are generated. Other ventilation systems are activated manually by the occupant and may not run enough to effectively remove pollutants, or may not even run at all.

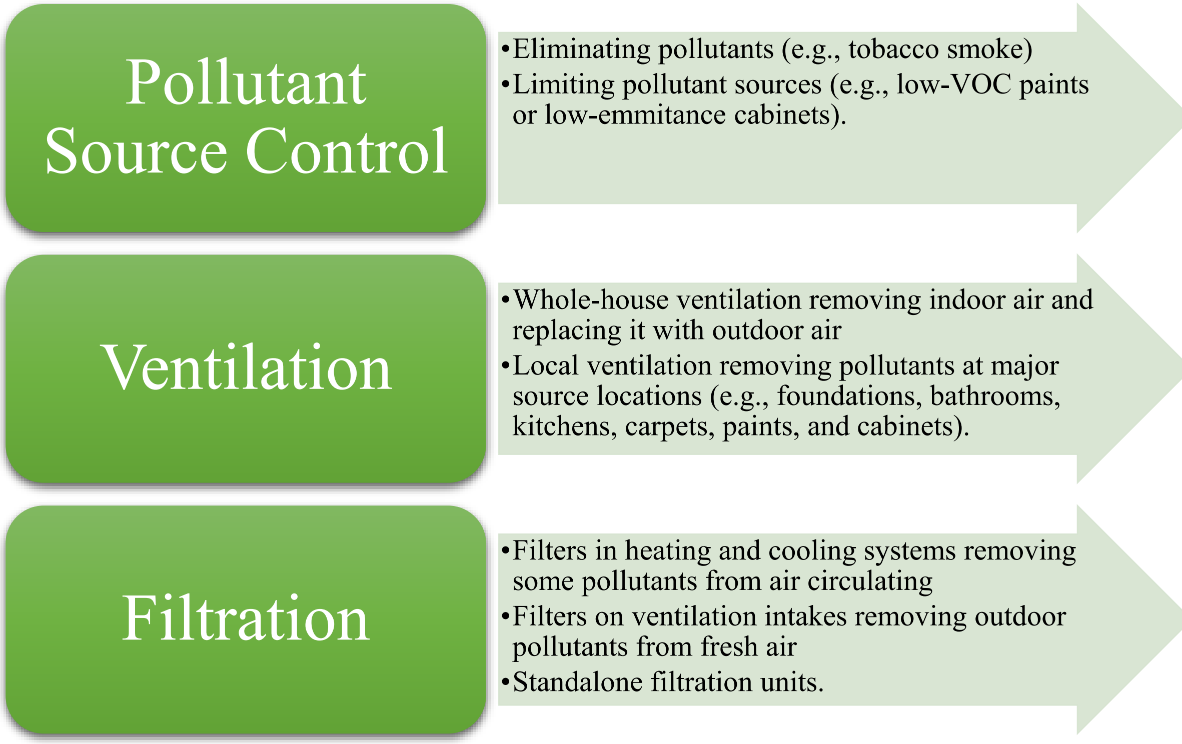

Figure 1. Primary approaches to dealing with indoor air pollutants

Adding a fourth IAQ tool—IAQ sensors—may work well as a compliment to the other three tools. Examples of sensor-driven IAQ solutions could include:

- Local mechanical ventilation controlled by sensors designed to detect the presence of pollutants. An example of this would be a system that senses the presence (or increase) of particulate matter and activates a range hood to remove pollutants from a kitchen. Another example would be a system that senses the presence of humidity indoors and uses ventilation to remove humidity and introduce dryer air.
- Whole-house mechanical ventilation controlled to activate exchange, exhaust, or supply of air (depending on system design) based on the presence of sensed indoor pollutants. These systems can also be controlled to deactivate based on a decrease in pollutants to operate more efficiently than an "always on" system.
- Whole-house mechanical ventilation controlled based on exterior conditions (temperature or humidity) that would be deactivated to stop introducing pollutants during a wildfire smoke event. In this example, a sensor might be located on the intake duct for ventilation systems.
- IAQ alerts that indicate when filters are full and need to be replaced to effectively filter pollutants.

- IAQ alerts using sensors to indicate when spaces are over-occupied and could present conditions conducive to aerosolized viral transmission.

1.1 Problem Statement

Sensors present an important opportunity to enhance indoor air quality in spaces such as homes, schools, offices, gyms, retail, etc., by providing dynamic information about the presence of indoor pollutants. For example, home occupants alerted to the presence of an indoor air pollutant might boost ventilation, change heating and cooling filters, activate air purifiers, or even leave the space until sensors indicate lower levels of pollutants. Controls could be designed to automatically control ventilation in a dynamic way that saves energy when indoor air pollutants are not present and increases ventilation rates when needed in response to an indoor pollutant event. Schools could use indoor air quality sensors to determine whether occupancy in a space is high enough to present an increased risk of germ exposure for students. Factories that generate particulate matter (PM) could monitor worker safety conditions. The applications for real-time feedback and response to indoor air quality conditions are numerous and all have the potential to improve human health through improved indoor environments.

Rigorous requirements and testing protocols for a variety of air pollutants, established by the U.S. Environmental Protection Agency (EPA), called the Federal Reference Method (FRM) and Federal Equivalent Method (FEM), are used to evaluate air quality monitors. The FRM and FEM requirements are established in the *Code of Federal Regulations (CFR) 40 Part 53*. FRM and FEM designations are intended for ambient (outdoor) air monitors covering regulated pollutants such as PM over multiple sizes as well as several gases such as sulfur dioxide (SO_2), nitric oxide (NO), NO_2, and ozone (O_3). Due to the rigor of federal requirements, monitors receiving either of these designations are expensive, research-grade monitors, costing thousands of dollars—making their use in residential consumer applications, or even commercial applications, impractical. To be used for indoor applications in homes, workplaces, etc., sensors need to be low-cost enough for everyday use. In fact, many manufacturers do not currently list prices for their products, requiring interested parties to request a quote, making the market inaccessible to consumers (CFR 40 Part 53).

Low-cost indoor air quality sensors, including sensor systems with multiple sensors, are widely available on the market, with hundreds of devices for purchase from several dollars to a few hundred dollars. These devices are widely and easily available for order direct from the manufacturer or through big box and online retailers. Many devices detect, or claim to detect, multiple pollutants and can provide direct feedback or can be synced with a variety of smart devices.

Many sensor systems provide consumer apps for easy access to the sensor data. These sensors are marketed for a variety of purposes, with many manufacturers focusing on providing feedback devices to inform occupants about their indoor air quality. Other sensor manufacturers have partnered with ventilation manufacturers to develop systems to dynamically control ventilation based on pollutant concentrations (U.S. DOE 2016). Some leading innovative residential builders have installed custom sensor arrays in their homes to create dynamic ventilation systems or to validate their indoor air quality claims for their buyers (U.S. DOE 2023).

Recently, during the COVID-19 pandemic, IAQ sensors received increased attention for their potential to evaluate viral load in a space (either directly through particle sensing, or indirectly by using CO_2 as a proxy for viral load). While not a definitive study, the American Chemical Society published a study, *Exhaled CO_2 as a COVID-19 Infection Risk Proxy for Different Indoor Environments and Activities*, examining the use of CO_2 sensors as viral detectors (Peng and Jimenez 2021). The study did not show a direct connection between actual CO_2 concentrations and viral load, which was dependent on multiple factors, such as level of activity. The study did find that monitoring CO_2 levels and ventilating to keep CO_2 in a space low was likely to reduce viral load in the space. While no definitive research establishes this approach as a valid viral mitigation or detection method, consumers and business owners have used these sensors for that purpose, with no real assurance of the sensors' accuracy.

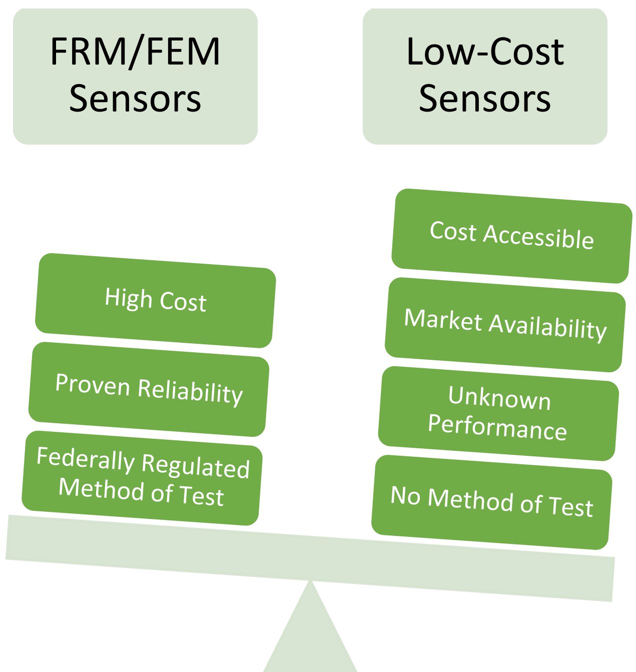

Figure 2. FRM/FEM sensors versus low-cost sensors

A primary barrier to using low-cost IAQ sensors to improve IAQ, or to provide reliable information on IAQ status in indoor environments, is that there has been no established method for determining how well low-cost sensors work. In fact, early studies (see Literature Review and Previous Work) suggested that there may be broad variability in the ability of these sensors to accurately measure pollutant concentrations, or even to credibly track changes in pollutant levels that would suggest the need for action. In some cases, sensors are reporting one pollutant while using a different pollutant to act as a proxy for that substance, performing no actual measurement of the pollutant of concern.

Manufacturers perform their own testing, but this testing varies across private organizations and does not carry with it the credibility of testing performed to a consensus standard. Without any way to reliably evaluate low-cost sensors, the ability to use them to improve indoor air quality may be limited. A standardized method of testing is needed to evaluate sensors and sensor units in a way that is reliable and comparable to other sensors.

1.2 Objectives

The objective of this project is to develop laboratory test methods for evaluation of low-cost IAQ sensors and provide technical support to industry stakeholders during the development of an American Society for Testing and Materials (ASTM) standard based on these test methods. The desired outcome is supporting the development of dependable smart ventilation systems that rely on accurate, low-cost IAQ sensors to safeguard occupant health while minimizing energy use.

Specifically, the project team worked to develop initial laboratory test methods for two pollutants with the goal that these test methods could then be used as models for sensors of other pollutants. Particles and gases represent two major categories of pollutants encountered in indoor environments. By choosing one of each, it is likely that many of the approaches for each model pollutant will be applicable, or adaptable, for other pollutants in that same class. Therefore, the two priority pollutants will act as models for future test method development. For this reason, the project focused on developing a test method for one particle or aerosol size, in addition to one gas, with the hope that future test methods for particles of other sizes, as well as different gases, will benefit from the technical detail of the early test methods, while updating technical approaches appropriately to match these different substances.

Key evaluation parameters of the test methods include:

- Correlation to FEM reference monitor
- Accuracy
- Precision
- Effect of interferents
- Climatological stability
- Drift.

1.3 Research Questions

- Can proprietary test procedures for evaluating IAQ sensors be transitioned to fully vetted test methods that can be published as consensus test standards?
- Can test methods be published for sensors of one aerosol-type pollutant ($PM_{2.5}$) and one gas-type pollutant (CO_2) that can then be used as models for future test methods for sensors of other pollutants?
- Can adequate stringency be incorporated into test methods for $PM_{2.5}$ and CO_2 that provide repeatability and reliability while minimizing testing cost and gaining broad consensus buy-in through the ASTM process?
- Can key criteria for IAQ performance be evaluated, such as correlation using the Pearson linear coefficient of determination with FEM reference monitor, bias, precision of the test sensor (percent relative standard deviation), interference, drift after one year of use (compared to new equipment), and response to varying levels of temperature and relative humidity?

1.4 Literature Review and Previous Work

This section provides an overview of recent research related to evaluation of low-cost IAQ sensors. Significant interest in the use of low-cost indoor air quality sensors for a variety of purposes, a growing market of sensor models and options available to consumers, and a lack of standardized performance data has led to multiple studies attempting to evaluate sensor performance.

As part of their work studying and monitoring air quality, the South Coast Air Quality Management District (South Coast AQMD) created the Air Quality Sensor Performance Evaluation Center (AQ-SPEC) to "inform the public of commercially available 'low-cost' air quality sensors." (AQ-SPEC 2022) AQ-SPEC developed a prototype test chamber intended to be used to compare low-cost sensors with research grade reference monitors to evaluate the relative performance of the low-cost sensors. AQ-SPEC also developed the preliminary test procedures that would eventually serve as the basis for developing standard test methods. Their work is detailed in *Development of an Environmental Chamber for Evaluating the Performance of Low-Cost Air Quality Sensors Under Controlled Conditions* (Papapostolou et al. 2017) and *Laboratory Evaluation of Low-Cost Air Quality Sensors Laboratory Setup and Testing Protocol* (Polidori, Papapostolou, and Zhang 2016). AQ-SPEC's idea to use a chamber with reference monitors was an important step toward being able to evaluate low-cost sensors. Using this approach, the laboratory can evaluate sensors under a variety of controlled conditions and can establish specific pollutant concentrations within the chamber system, better understanding the pollutant concentrations that the sensors should be recording. Most other work evaluating sensors has relied on "field testing" or on laboratory testing in open environments, such as on a cook top. While this approach may offer a more direct comparison to real-world scenarios, it has the drawback of not being able to reliably control the pollutant concentration during the test.

A limited study of three sensors was conducted by the Biswas Group, *Laboratory Evaluation and Calibration of Three Low-Cost Particle Sensors for Particulate Matter Measurement* (Wang et al. 2015), using a similar technique of comparing low-cost sensors to reference monitors in a chamber system. In this case, the study only examined PM sensors. Like the AQ-SPEC approach, the study evaluated performance of low-cost sensors when exposed to different pollutant concentrations and varying conditions. The study found that particle source and size had an impact on performance of the sensors. One drawback to the study was that measurements were not taken at steady state. While average measurements were recorded, the particle generation was not constant throughout the experiment. A benefit of the AQ-SPEC approach, and later the published test method, was that it compares pollutant concentration data of low-cost sensors and reference monitors only during steady-state conditions so that it is known exactly what the low-cost sensor should be experiencing according to the reference monitor.

In 2013, a European protocol was developed for testing low-cost sensors. *Protocol of Evaluation and Calibration of Low-Cost Gas Sensors for the Monitoring of Air Pollution* (Spinelle, Aleixandre, and Gerboles 2013) was intended specifically to test ambient (outdoor) air sensors, rather than indoor air sensors. The study found that accuracy of data could be improved by averaging test results over time due to fluctuations in PM. The approach is similar to that used by AQ-SPEC and studied NO_2 and O_3 gas sensors. Unlike the published test method developed during this project, drift was entirely estimated through calculation rather than artificially aging the sensors and then extrapolating drift.

Demanega et al. (2021) authored "Performance Assessment of Low-Cost Environmental Monitors and Single Sensors under Variable Indoor Air Quality and Thermal Conditions," a report describing their experiment testing 8 low-cost sensors or sensor systems by exposing them to PM, CO_2, and tVOC over 16 different runs. The experiment used a conference room instead of a chamber, and used a variety of methods for generating PM, such as burning candles and vacuuming. The study showed a wide variety in performance among the tested sensors in these conditions, although sensors did seem to register real-time changes in particle concentrations. In a similar study in 2020, Lawrence Berkeley National Laboratory evaluated low-cost PM sensors. Wang, Delp, and Singer (2020) authored "Performance of Low-Cost Indoor Air Quality Monitors for $PM_{2.5}$ and PM_{10} from Residential Sources," which evaluated a variety of natural PM sources including a range of cooking scenarios. The use of real-world particle sources in both studies provides important data on how sensors react differently depending on particle source and helped inform development of the $PM_{2.5}$ test method, which includes both an organic and inorganic particle during the test. While using organic particles for most phases of this test is not practical for a standardized test method due to broad variations in pollutant concentrations that can be generated, this study reinforces the need for both organic and inorganic particle analysis to play some part in the test method.

A similar study was conducted as an American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASRHAE) research project that evaluated the responses of eight different sensor systems compared to a reference monitor as they experienced particle emissions from a variety of sources (Zou, May, and Clark 2021). As with other studies, the performance of low-cost sensors varied significantly, but they performed better at recording change in particle concentrations than they did at recording absolute concentrations accurately when compared to the reference monitor.

Moreno-Rangel et al. (2018) authored "*Field Evaluation of a Low-Cost Indoor Air Quality Monitor to Quantify Exposure to Pollutants in Residential Environments*," which compared low-cost sensors to a reference monitor in a residential setting. This study followed an existing ASTM standard for evaluating IAQ in a space. The existing standard is not meant to test sensors, but rather to evaluate the actual conditions in a space. Sensors experienced uncontrolled exposure to pollutants occurring in the occupied space. The study showed better performance of the low-cost sensor when measuring tVOC or PM than CO_2. Part of the reason for this is that the sensor system being tested used tVOC as a proxy for CO_2 rather than directly measuring CO_2. These field evaluations, while valuable, all have the same problem of not being able to evaluate sensors under specific repeatable conditions, a centrally important aspect of the test methods developed as part of this project.

2 Methodology

This project was not a typical research project in that the overall purpose was not to test a specific hypothesis or compare various approaches at reaching a technical goal. Instead, it was to provide technical support to a consensus and standard development process. Because of this, the methodology section focuses on the following:

- The process and methodology for developing test method drafts
- The ASTM standard test method process and methodology
- The technical methodology used in the test method drafts
- Lab testing approach to evaluating the feasibility of the methodology.

2.1 Draft Test Method Development Process and Methodology

Figure 3 shows the main steps used in our method development process.

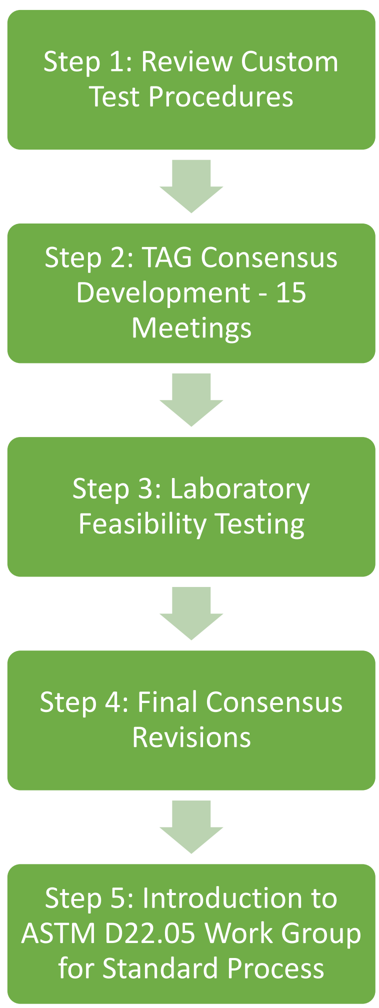

Figure 3. Overview of project process

The IAQ test method drafts were initially developed by using procedures developed by the South Coast AQMD's AQ-SPEC. These procedures are detailed in "*Development of an Environmental Chamber for Evaluating the Performance of Low-Cost Air Quality Sensors Under Controlled Conditions"* (Papapostolou et al. 2017), which details the initial procedure as well as equipment specifications for their custom test chamber and instruments. These procedures acted as an important technical basis for test method development. However, the language had to be rewritten into enforceable language that could be accepted as part of a standards process. In addition, careful consideration was needed in deciding how prescriptive or performance-based the method should be.

More prescriptive methods, with each small detail set in the standard, are easy to follow and repeat. However, this approach can limit the ability of other laboratories to use the test method, even if they could create the same conditions with different equipment or approaches. For example, the chamber volume for testing sensors will affect how much pollutant needs to be introduced into the chamber, the fan speed for mixing pollutants, and the time the test will take.

The procedures also needed to be vetted with a broader stakeholder audience to determine whether industry would use the standard and whether end users would accept the results as reliable and robust. To help shape the procedures into draft test methods, Newport gathered a Technical Advisory Group (TAG) of stakeholders and conducted an informal consensus process of technical review. The purpose of this review was to transform the original test procedures into an enforceable and defendable draft test method.

The TAG also worked with the goal of solving as many objections as possible that might be encountered during the formal ASTM process. The TAG, which met 15 times from 2018–2020, was made up of a variety of stakeholders representing the groups shown in Table 1. Examples of major TAG decisions that influenced the draft prior to ASTM process are shown in Figure 4.

Table 1. Technical Advisory Group Stakeholders

Government Agencies	Laboratories	Ventilation Industry	Sensor Industry	Other
U.S. Department of Energy	Lawrence Berkeley National Laboratory	Home Ventilating Institute		Indoor Air Quality Experts
U.S. Environmental Protection Agency	South Coast AQMD AQ-SPEC	Healthy Air Research and Certification Authority	8 Sensor or Sensor System Manufacturers	Sensor Experts
National Institute for Standards and Technology	Texas A&M Riverside Energy Efficiency Laboratory	3 Ventilation Manufacturers		Interested Members of ASTM D22.05 Subcommittee

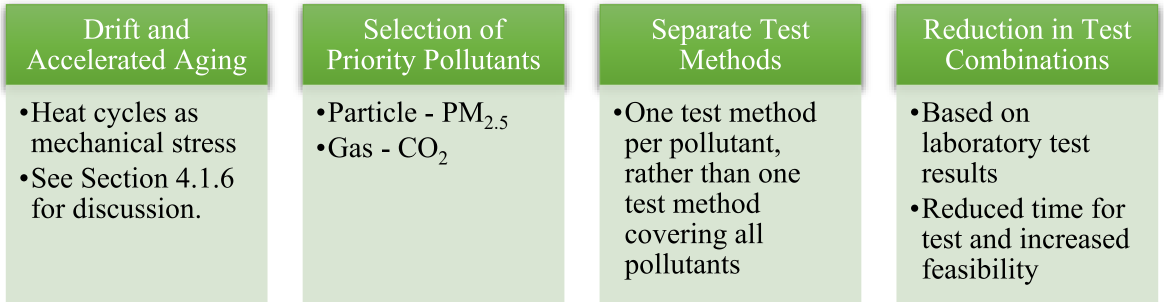

Figure 4. Examples of major Technical Advisory Group decisions

2.2 ASTM Process and Methodology

2.2.1 Overview

The ASTM standard development process is created with the intent of developing a consensus standard that also meets strict requirements for scientific rigor. This section provides a high-level overview of the process that this project's test methods will go through for approval, as well as a summary of the technical support activities that the project team provides. The ASTM process is summarized in Figure 5.

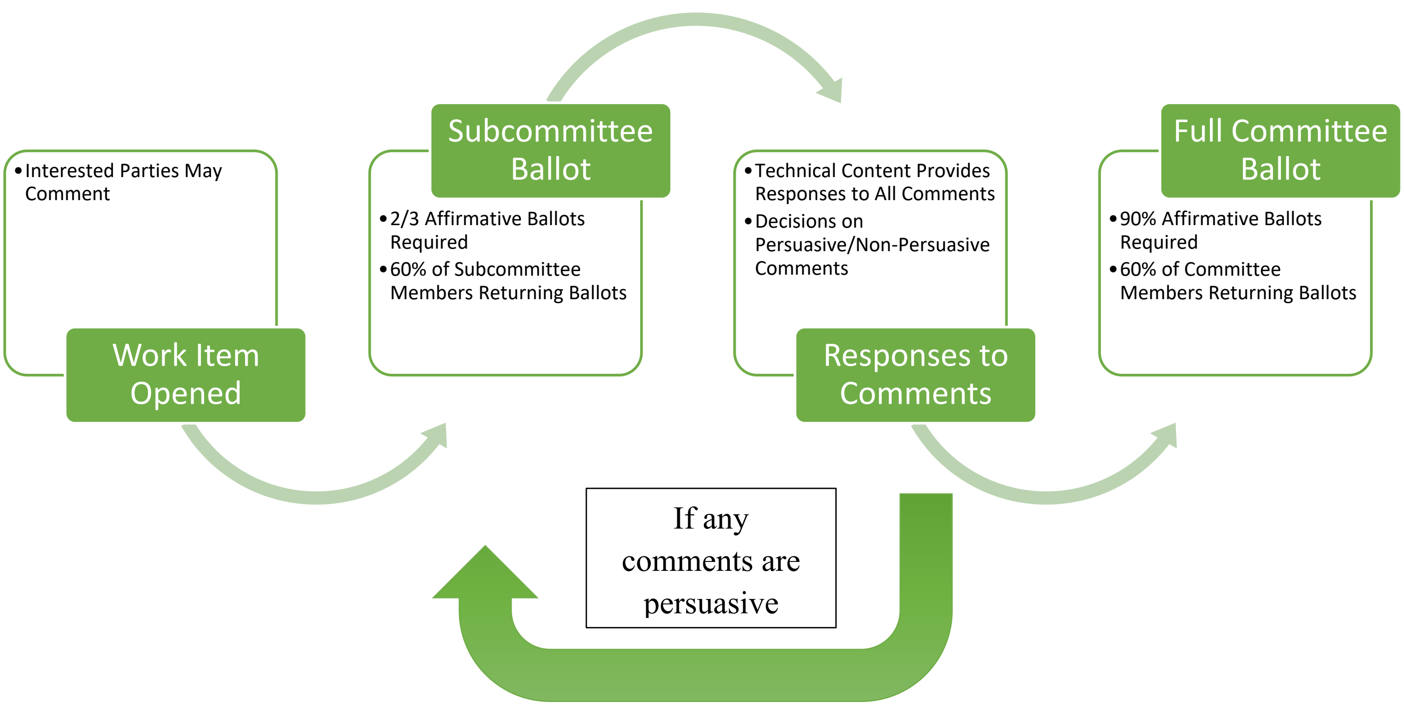

Figure 5. ASTM process overview

Draft standards often go through multiple ballots as corrections are made and consensus is developed within the subcommittee and then the full committee. The test methods in this project were introduced into the ASTM D22.05 Subcommittee on Indoor Air, which is part of the ASTM D22 Committee on Air Quality. Newport proposed a work item with the ASTM D22.05 Subcommittee in coordination with the proposal for this project. In April 2017, the subcommittee voted to open a work item related to development of IAQ sensor test methods, with Newport as the technical lead on the work item.

Any test method submitted to ASTM for publication must have laboratory testing to demonstrate that it is feasible to generate the test conditions as described in the method, as well as to develop information regarding precision and bias of the test method and to describe reproducibility limits and repeatability limits of the method. The test method will also eventually need to conduct inter-laboratory testing. Initial testing of each test method was conducted before introducing the draft to ASTM.

Once a draft test method is submitted for ballot, subcommittee or committee members vote on each item. At any point in the ASTM process, committee members can raise objections or make suggestions that the technical lead on any draft standard will need to address. All comments received through negative ballots must be resolved either through changes or through a vote. If any comment (negative or affirmative) is found to be persuasive, the ballot is withdrawn, and the item is revised and resubmitted.

2.3 Test Method Technical Methodology

Figure 6. AQ-SPEC prototype chamber

Photo Credit: South Coast Air Quality Management District

The process designed in the test method uses a chamber system into which sensors or sensor systems are placed along with sampling probes for reference monitors. The reference monitors used in this chamber were selected based on their FEM designation. Pollutants are introduced into the chamber system, and tested sensors are compared to reference monitors at steady-state conditions. This means that when the reference monitor indicates that pollutant concentrations have reached steady state, the reference monitor's concentration measurements are compared to corresponding measurements of the test sensors.

Steady state is reached when the reference monitor reaches the pollutant concentration targets within a prescribed percent relative standard deviation limit (tolerances vary based on pollutant and concentration) over 20 consecutive measurements. A minimum of 20 measurements at each test point are compared. The time this will take varies by the chamber and the time resolution of the reference monitor and test sensor. The 20 measurements are based on the longer of the time resolution of the test sensor and the reference monitor. The reference monitor is required to have a time resolution of 1 minute or less, so measurements at steady state will take at least 20 minutes to measure. However, if the test sensor had a time resolution of 2 minutes, this time would double to record 20 measurements. This process is used to compare test sensors to the reference monitor under a variety of conditions including different pollutant concentrations, varying combinations of temperature and relative humidity, and the introduction of interferents (different for each pollutant) into the chamber. The test also uses an accelerated aging process and then reevaluates the sensors at varying pollutant concentrations to measure drift after one year of use.

A photo of the AQ-SPEC chamber prototype can be seen in Figure 6, and Figure 7 shows a diagram that depicts the AQ-SPEC chamber prototype. In this example, the chamber system includes functionality for PM sensor testing, including both $PM_{2.5}$ and PM of 10 micrometers or smaller (PM_{10}) in the larger, outer chamber. The chamber also includes functionality for testing gas sensors in the smaller inner chamber. In addition to CO_2, the AQ-SPEC chamber is equipped to test sensors for CO, nitrogen oxides (NOx), O_3, SO_2, hydrogen sulfide (H_2S), and hydrocarbons. The inner chamber in this system can be replaced with a modified inner chamber for more specific testing of VOC sensors. This chamber is significantly more advanced than most laboratories will need to develop to perform an IAQ sensor test method because it can test sensors for multiple pollutants. The test methods are separated by pollutant, so that any laboratory with the ability to test sensors for one pollutant could perform that test, without needing reference monitors, scrubbers, and other supplies necessary for testing sensors of different pollutants. Diagrams depicting only the required equipment for each test method are published by ASTM in the test method.

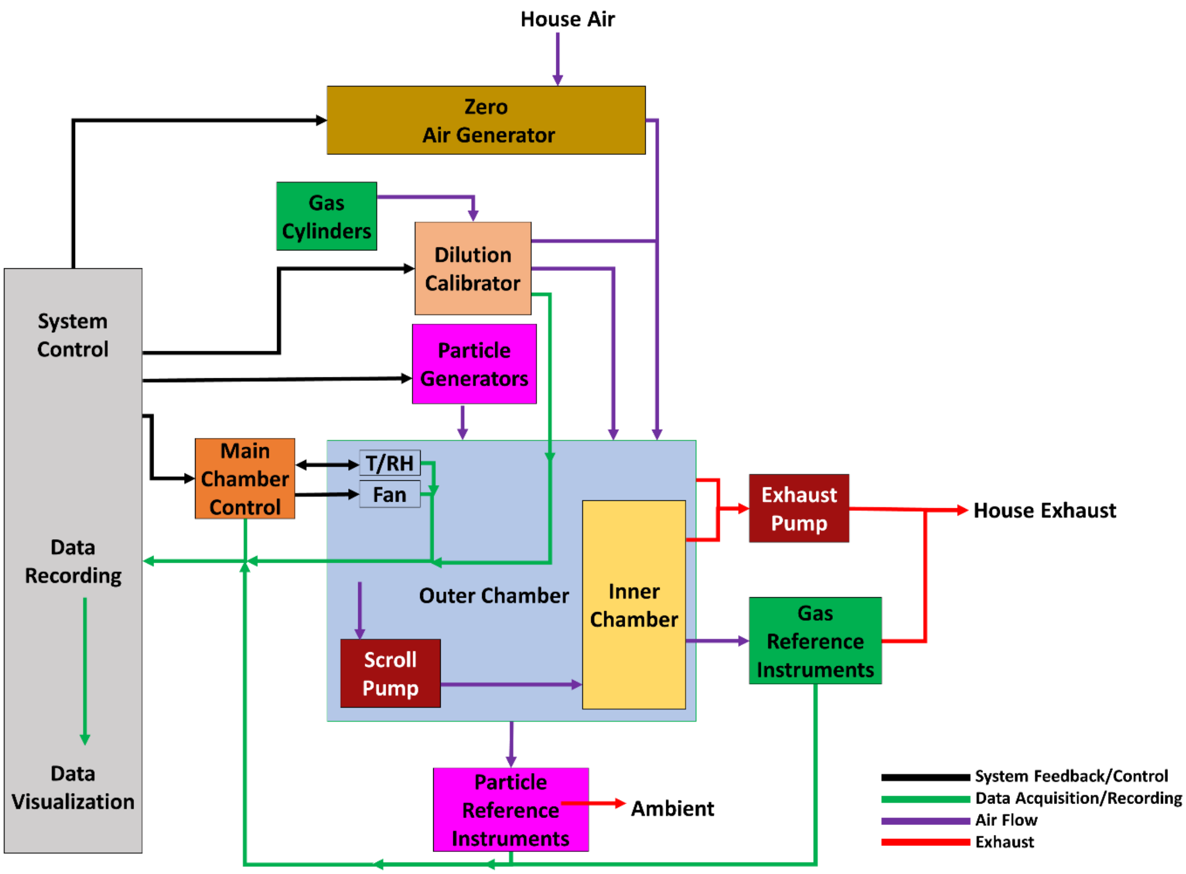

Figure 7. Diagram of AQ-SPEC chamber system

Image Credit: South Coast Air Quality Management District

2.3.1 $PM_{2.5}$ Test Method Overview

Table 2. Overview of Target Conditions in $PM_{2.5}$ Sensor Test

Phase 1: Initial Concentration Ramping						
Test Combinations	Limit of Detection 20°C 40% RH	10 (µg/m^3) 20°C 40% RH	15 (µg/m^3) 20°C 40% RH	50 (µg/m^3) 20°C 40% RH	150 (µg/m^3) 20°C 40% RH	300 (µg/m^3) 20°C 40% RH
Phase 2: Effect of Temperature and Relative Humidity						
Test Combinations	10 (µg/m^3) 20°C 40% RH	50 (µg/m^3) 20°C 40% RH	10 (µg/m^3) 20°C 40% RH	50 (µg/m^3) 20°C 40% RH	10 (µg/m^3) 20°C 40% RH	50 (µg/m^3) 20°C 40% RH
	10 (µg/m^3) 30°C 60% RH	50 (µg/m^3) 30°C 60% RH	10 (µg/m^3) 30°C 60% RH	50 (µg/m^3) 30°C 60% RH	10 (µg/m^3) 30°C 60% RH	50 (µg/m^3) 30°C 60% RH
	10 (µg/m^3) 50°C 80% RH	50 (µg/m^3) 50°C 80% RH	10 (µg/m^3) 50°C 80% RH	50 (µg/m^3) 50°C 80% RH	10 (µg/m^3) 50°C 80% RH	50 (µg/m^3) 50°C 80% RH
Phase 3: Particle Size Interferent Testing						
Test Combinations		10 (µg/m^3) 20°C 40% RH	15 (µg/m^3) 20°C 40% RH	50 (µg/m^3) 20°C 40% RH	150 (µg/m^3) 20°C 40% RH	300 (µg/m^3) 20°C 40% RH
Phase 4: Temperature Cycling						
143 Cycles			10°C–50°C			
Phase 5: Final Concentration Ramping						
Test Combinations	Limit of Detection 20°C 40% RH	10 (µg/m^3) 20°C 40% RH	15 (µg/m^3) 20°C 40% RH	50 (µg/m^3) 20°C 40% RH	150 (µg/m^3) 20°C 40% RH	300 (µg/m^3) 20°C 40% RH

The negative health effects of $PM_{2.5}$ on humans, including cardiovascular and respiratory issues, have been thoroughly researched and well-documented over several decades. In *Clearing the Air: A Review of the Effects of Particulate Matter Air Pollution on Human Health*, Anderson, Stolbach, and Thundiyil (2012) found that studies consistently showed a broad negative health impact from PM, especially cardiovascular and respiratory impacts. The California Air Resources Board estimates that thousands of premature deaths in the state each year are caused by $PM_{2.5}$ contributing to cardiovascular and respiratory health problems (California Air Resources Board 2010). Although these estimates are based on ambient air exposure, $PM_{2.5}$ is also generated by common indoor sources, such as cooking (Kang et al. 2019). Due to the well-documented dangers of indoor $PM_{2.5}$, this pollutant was chosen as the first priority particle or aerosol for test method development.

The published $PM_{2.5}$ test method, *ASTM D8405-21 Standard Test Method for Evaluating $PM_{2.5}$ Sensors or Sensor Systems Used in Indoor Air Applications*, contains five testing phases, summarized in Figure 8, in which sensor models are evaluated in triplicate for their ability to measure $PM_{2.5}$ concentrations and compared to the pollutant concentrations measured by a reference monitor while the chamber is under steady-state pollutant concentration conditions. Phase 1 concentration ramping tests sensors' responses to six different concentrations of $PM_{2.5}$, ranging from the lower limit of detection of the reference monitor through 300 µg/m^3. Phase 1 is performed twice, first using sodium chloride (NaCl), an inorganic particle, and then using polystyrene latex (PSL) spheres, an organic particle. Phase 1 is performed at a constant temperature and relative humidity. The remainder of the test phases only use NaCl as the $PM_{2.5}$ source. Phase 2 tests the effect of varying combinations of temperature and relative humidity on the sensor's performance. Phase 2 tests up to nine combinations of temperature and relative humidity at a steady $PM_{2.5}$ concentration. Phase 3 tests the effect of interferents on the sensors. In this case, interferents used are other particle sizes up to 10 µm. Phase 3 tests sensors at four different interferent particle concentrations. Phase 4 does not test sensors with pollutants present. It performs a temperature cycling as a method of accelerated aging by simulating mechanical stress. Finally, Phase 5 repeats the concentration ramping phase (only with NaCl) to measure sensor drift after 1 year of simulated use.

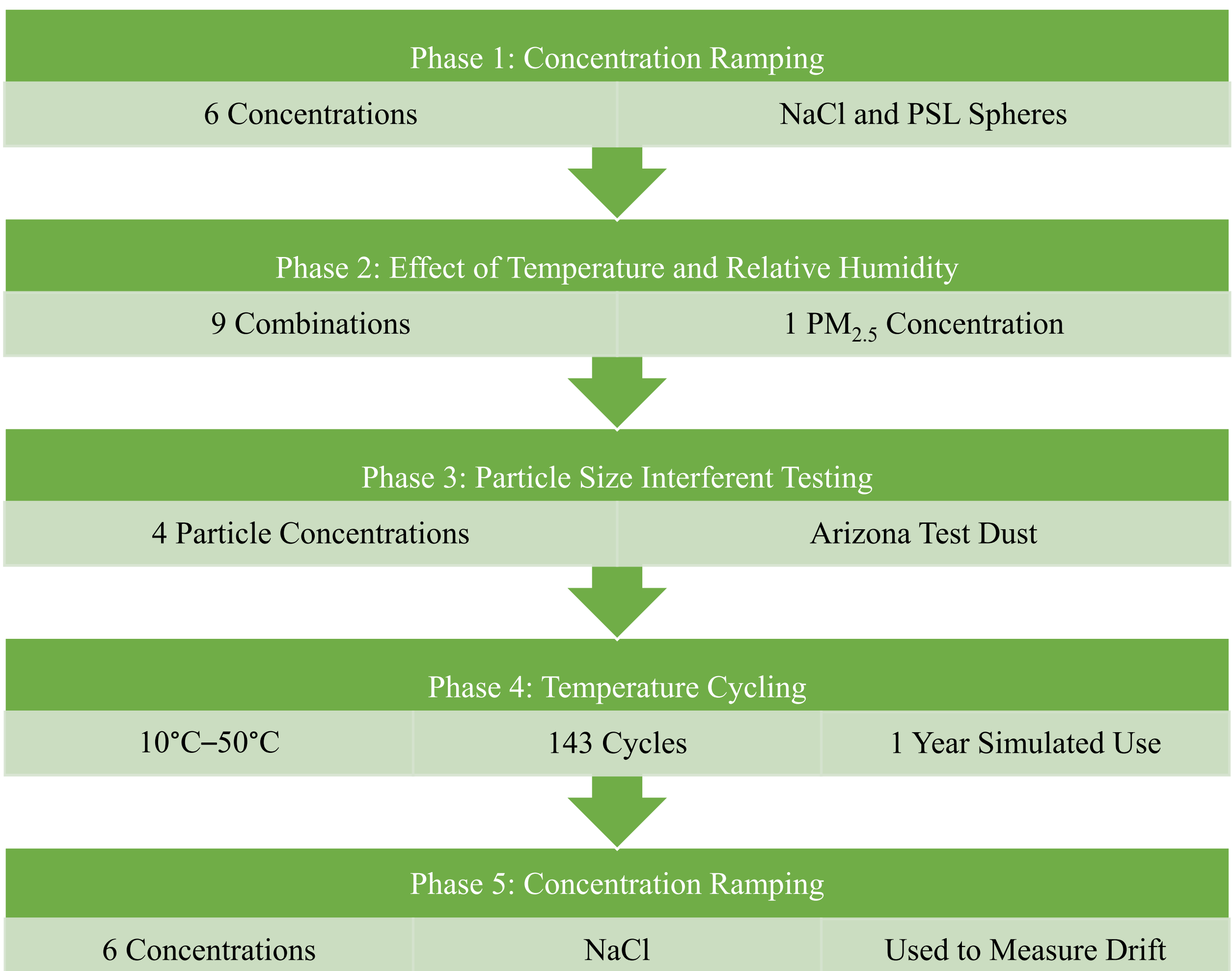

Figure 8. Summary of $PM_{2.5}$ test method

Table 3. Overview of Target Conditions in CO_2 Sensor Test

Phase 1: Initial Concentration Ramping						
Test Combinations		450 PPM 20°C 40% RH	1,000 PPM 20°C 40% RH	2,000 PPM 20°C 40% RH	3,000 PPM 20°C 40% RH	5,000 PPM 20°C 40% RH
Phase 2: Effect of Temperature and Relative Humidity						
Test Combinations	1,000 PPM 20°C 40% RH	5,000 PPM 20°C 40% RH	1,000 PPM 20°C 40% RH	5,000 PPM 20°C 40% RH	1,000 PPM 20°C 40% RH	5,000 PPM 20°C 40% RH
	1,000 PPM 30°C 60% RH	5,000 PPM 30°C 60% RH	1,000 PPM 30°C 60% RH	5,000 PPM 30°C 60% RH	1,000 PPM 30°C 60% RH	5,000 PPM 30°C 60% RH
	1,000 PPM 50°C 80% RH	5,000 PPM 50°C 80% RH	1,000 PPM 50°C 80% RH	5,000 PPM 50°C 80% RH	1,000 PPM 50°C 80% RH	5,000 PPM 50°C 80% RH
Phase 3: Relative Humidity Interferent Testing						
Test Combinations		1,000 PPM 20°C 20% RH	1,000 PPM 20°C 40% RH	1,000 PPM 20°C 60% RH	1,000 PPM 20°C 75% RH	1,000 PPM 20°C 80% RH
Phase 4: Temperature Cycling						
143 Cycles			10°C–50°C			
Phase 5: Final Concentration Ramping						
Test Combinations		450 PPM 20°C 40% RH	1,000 PPM 20°C 40% RH	2,000 PPM 20°C 40% RH	3,000 PPM 20°C 40% RH	5,000 PPM 20°C 40% RH

2.3.2 CO_2 Test Method Overview

While the dramatic health effects of $PM_{2.5}$ are not associated with CO_2 exposure, increased indoor CO_2 has been associated in several studies with decreased cognitive function (Allen et al. 2016; Satish et al. 2012). A Lawrence Berkeley National Laboratory study on CO_2 and Sick Building Syndrome (SBS) found "statistically significant associations of mucous membrane and lower respiratory SBS symptoms" with increased indoor CO_2 levels. "[T]here is no direct causal link between exposure to CO_2 and SBS symptoms, but rather CO_2 is approximately correlated with other indoor pollutants that may cause SBS symptoms" (Erdmann, Steiner, and Apte 2002). In addition to any possible negative health effects of indoor CO_2 exposure, CO_2 has been used as a proxy both for human occupancy in a space, and for the possible existence of other pollutants in a space. For this reason, CO_2 sensor applications have been considered for use in demand-controlled ventilation. In addition to the use of CO_2 sensors in commercial settings to control ventilation systems, several builders in the DOE Zero Energy Ready Home program have begun using custom sensor arrays in residential applications to control ventilation systems. Due to the industry interest in using CO_2 levels as an indicator for ventilation, and the existence of a variety of low-cost CO_2 sensors, CO_2 was chosen as the priority gas pollutant for initial test method development.

The draft CO_2 test method currently contains five testing phases, summarized in Figure 9, in which sensor models are evaluated in triplicate for their ability to measure CO_2 concentrations and compared to the CO_2 concentrations measured by a reference monitor under steady-state CO_2 concentration conditions. Phase 1 concentration ramping tests sensors' response to five different concentrations of CO_2, from 450 parts per million (PPM) to 5,000 PPM. While typical ambient CO_2 concentrations might range from 300–900 PPM, indoor concentrations are often encountered at much higher levels. Drowsiness, cognitive difficulties, and other health effects have been encountered between 1,000 and 5,000 PPM, and the Occupational Safety and Health Administration sets workplace limits of 5,000 PPM. For this reason, a range of 450 PPM–5,000 PPM was chosen. Although concentrations can be much higher and reach dangerous levels, 5,000 PPM would represent an acute event warranting intervention (ventilation, etc.) (U.S. Department of Agriculture 2020).

Phase 1 is performed at a constant temperature and relative humidity. Phase 2 tests the effect of varying combinations of temperature and relative humidity on the sensor's performance. Phase 2 tests up to nine combinations of temperature and relative humidity at a steady CO_2 concentration. Phase 3 tests the effect of interferents on the sensors. In this case, the interferent used is relative humidity. Phase 3 tests sensors at five different relative humidity levels, while the CO_2 concentration is held constant. Phase 4 is not intended to test response to CO_2 concentrations; rather, it performs a temperature cycling as a method of accelerated aging by simulating mechanical stress. Finally, Phase 5 repeats the concentration ramping phase to measure sensor drift after 1 year of simulated use.

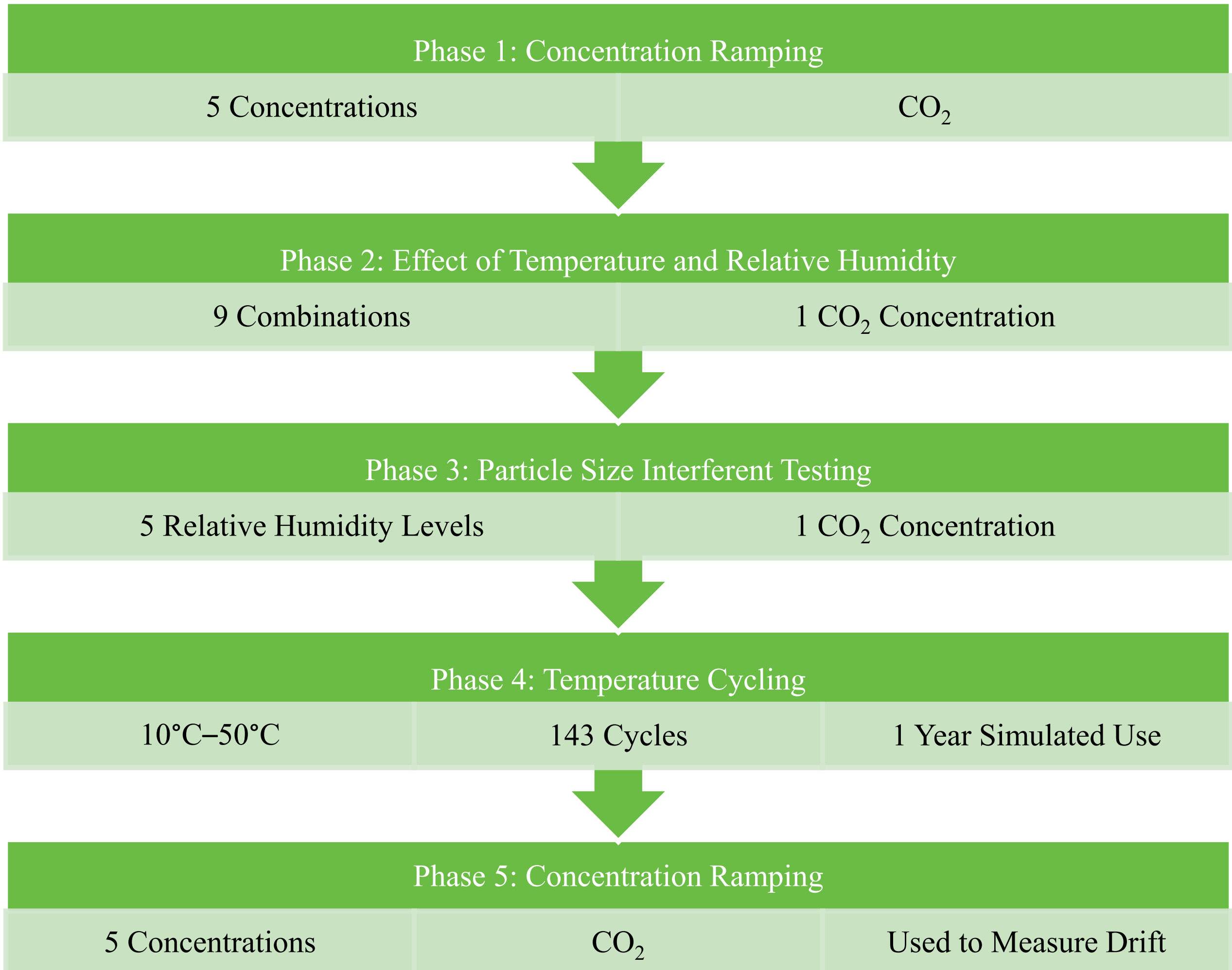

Figure 9. Summary of CO_2 test method

3 Results

This report details the consensus and technical process used to develop IAQ sensor test methods. The results are not the typical results of a research project. Rather, the results discussed fit into two categories:

- Results of laboratory testing
- Results of the ASTM consensus process.

Likewise, the laboratory testing was not focused on studying the specific performance of tested sensors. In fact, the sensors tested were kept anonymous because they were being used to establish the procedure. The purpose of the laboratory testing was to demonstrate the feasibility of the test method, and to demonstrate that the conditions described in the test method were achievable in a real chamber system. While we do report summaries of sensor performance when available, the results should not be interpreted as representative of the low-cost sensor market in general.

3.1 Summary of $PM_{2.5}$ Laboratory Testing Results

The primary goal of laboratory testing was to establish that the test conditions described in the draft could be achieved. This included the required range of temperature and relative humidity targets, along with the required $PM_{2.5}$ concentrations, within all the allowed tolerances as described in the test method (+/-10%). For the $PM_{2.5}$ test method, all these targets and tolerances are now published in *ASTM D8405-21*.

For a full and detailed report, the results are published in AQ-SPEC's laboratory report Evaluation Report for Four $PM_{2.5}$ Sensor Units Following the draft Standard Test Method for $PM_{2.5}$ Sensor Units Intended for Indoor Air Application (ASTM D22.05) (Mui, Kuang and Papapostolou 2019). In addition, ASTM published *Intralaboratory Study to Establish a Repeatability Statement for ASTM D8405-21, Test Method for Standard Test Method for $PM_{2.5}$ Sensors or Sensor Units Used in Indoor Air Applications* (ASTM 2021), which summarized the precision and bias of the method as demonstrated by single laboratory testing. Because these test results are published elsewhere, highlights of the testing are discussed here.

3.1.1 Tolerances

The initial, pre-testing draft included relative standard deviation (RSD) tolerances of +/- 4% for $PM_{2.5}$ concentrations as reported by the reference monitor. This measurement is intended to define steady state in the chamber. However, testing showed that this was not always a feasible target in the chamber system. As a result, the tolerances were increased to RSD of +/- 5% or +/- 10% depending on what was achievable at each concentration level. These tolerances were needed based on the chamber's ability to reach the target concentration levels as established by the reference monitor measurements. The conditions were not limited by the reference monitor's ability to accurately measure $PM_{2.5}$ levels, but rather by the chamber's ability to reach specific concentrations and hold them at steady state.

In addition, the initial draft did not include absolute tolerances. While pollutant concentrations were defined, and steady state was determined based on RSD, that RSD was not explicitly required to be close to the actual target concentration as initially written. According to the original draft, all that was required was to hit a steady-state condition without any description for the requirement to reach target concentrations within a certain tolerance. This was a detail that was overlooked in the text, rather than the intent of the draft, which was to define steady state based on relative standard deviation at specific concentrations. For this reason, an absolute tolerance of +/- 10% of the concentration in the test chamber as reported by the reference monitor was added as a requirement. For example, if 300 $\mu g/m^3$ was the target concentration, steady state could not be achieved regardless of RSD if the chamber stabilized at 150 $\mu g/m^3$. The absolute tolerance ensures that steady state is achieved at or near the desired concentration (Mui, Kuang and Papapostolou 2019; ASTM 2021).

3.1.2 Phase 1: Concentration Ramping Results

After establishing the tolerances that were achievable in the test chamber, low-cost test sensors performed well relative to the reference monitor in the initial concentration ramping. According to the AQ-SPEC evaluation report, "all test sensor models evaluated showed near-perfect correlation with the Reference Monitor during the Phase 1 initial concentration ramping." Test sensors followed the step increases at each concentration level; however differences in reported concentrations compared to the reference monitor were greater at higher concentrations (Mui, Kuang and Papapostolou 2019; ASTM 2021). Although the performance of the test sensors is not part of the research, the evaluation report includes the results for interested parties.

3.1.3 Phase 2: Effects of Temperature and Relative Humidity

Phase 2 testing exposed some of the physical limits of the draft test method during the laboratory testing. To achieve all temperature and relative humidity combinations at each pollutant concentration level, the testing would have taken months just to complete Phase 2. A test of that time length would prove impractical to use in the industry. For this reason, temperature targets were reduced from six to three to reduce testing time. The draft included testing at 15°C, 20°C, 30°C, 40°C, 50°C, and 60°C. The final test method included only 20°C, 30°C, and 50°C. Although fewer combinations were used, this still represents a likely range of common indoor conditions that a sensor might experience. Likewise, relative humidity targets were reduced from five to three to reduce test time and because the test chamber was unable to reliably reach relative humidity of 90% or higher. The draft included targets at 15%, 40%, 60%, 75%, and 90% relative humidity. The final test method only included 40%, 60%, and 80% relative humidity. Finally, the pollutant concentrations that were tested for each temperature and relative humidity combination were reduced from three to two to reduce testing time. The draft included testing at 10 $\mu g/m^3$, 50 $\mu g/m^3$, and 150 $\mu g/m^3$ pollutant concentrations. The final test method only included 10 µg /m^3 and 50 µg /m^3. With the exception of the 90% and 15% relative humidity targets, the changes in this phase were entirely driven by practical time limits required for testing, and not on the ability to reach specific targets. The effect on the test method is a decrease in necessary test time by weeks.

According to the AQ-SPEC evaluation report, "the climate susceptibility investigations in Phase 2 showed an increase in reported $PM_{2.5}$ concentrations at increased [temperature] above 20°C and [relative humidity] above 60% across all test sensor models" (Mui, Kuang, and Papapostolou 2019; ASTM 2021). Although the performance of the test sensors is not part of the research, the evaluation report includes the results for interested parties.

3.1.4 Phase 3: Particle Size Interferent Testing

The laboratory testing exposed a difficulty in achieving interferent phase testing conditions as originally written in the draft. Originally, the test method required particles of varying sizes to be introduced in a monodisperse method into the chamber while maintaining a background concentration of $PM_{2.5}$. However, it was not possible to measure both the $PM_{2.5}$ concentration and the interferent concentration accurately using this method. According to AQ-SPEC's evaluation report, "many attempts were made to try to accomplish these criteria, including using different particle materials (e.g., polystyrene latex spheres, silica spheres, ATD A4 powder), generation techniques (e.g., liquid suspension, dry powder dispersal), transport techniques (e.g., non-pressurized mixing and diffusion into the test chamber, pressurized injection into the test chamber), and separation techniques (e.g., virtual impaction to remove smaller particles). None were successful in providing monodisperse interferent particles above a concentration of 10 µg/m^3" (Mui, Kuang and Papapostolou 2019; ASTM 2021).

Because it was not possible to achieve test conditions using this method, the phase was edited to adjust the introduction of particles to use a polydisperse method. The revised method introduced particles ranging in size from $PM_{2.5}$ to PM_{10}, and the amount of interferent particle versus $PM_{2.5}$ was determined using a regression and was achievable during the test. Interferent particles introduced were Arizona Test Dust. According to AQ-SPEC's evaluation report, "the Phase 3 interferent testing showed that all the test sensor models underestimate $PM_{2.5}$ in the presence of interferent particles" (Mui, Kuang and Papapostolou 2019; ASTM 2021). Although the performance of the test sensors is not part of the research, the evaluation report includes the results for interested parties.

3.1.5 Phase 4: Temperature Cycling

No data are collected during Phase 4 of the testing. The chamber temperature is continuously cycled between 10°C and 50°C until the 143 cycles are complete. There are no intermediate temperature targets required by the test method as long as the cycle between minimum and maximum temperature is completed. During the laboratory testing, Phase 4 took 10 days to complete. This length of time will vary based on chamber size and temperature control equipment for individual laboratories. Because the temperature changes would likely have an effect on test sensor readings, and because the purpose of this phase is to age the sensors, no data are collected at this time. Any data during this phase would not be possible to accurately interpret, and the laboratory can save on material costs while not generating pollutants (Mui, Kuang, and Papapostolou 2019; ASTM 2021).

3.1.6 Phase 5: Final Concentration Ramping

Phase 5 testing repeats Phase 1 concentration ramping with the goal of measuring drift after artificially aging the sensors 1 year during Phase 4 of the testing. According to the AQ-SPEC's evaluation, "the Phase 5 drift test indicated that drift was minor for all test sensor models up to concentrations of 50 $\mu g/m^3$ but was drastically greater at concentrations above 150 $\mu g/m^3$" (Mui, Kuang, and Papapostolou 2019; ASTM 2021). Average drift, calculated across all three test sensors per model and experienced by the four sensor models, is depicted in Figure 10.

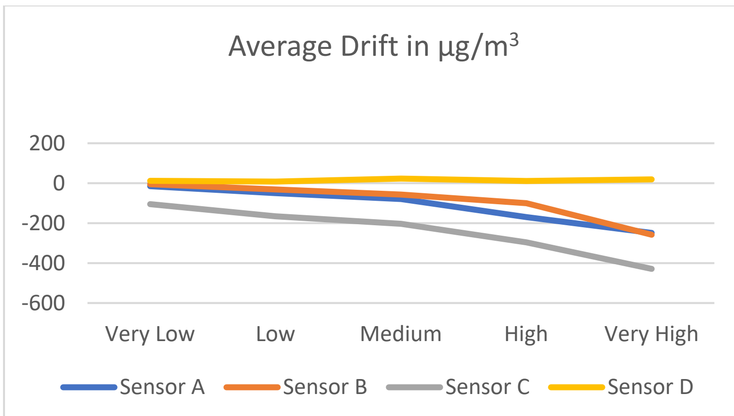

Figure 10. Average drift shown at test concentration levels

Source: Mui, Kuang, and Papapostolou 2019

Although the performance of the test sensors is not part of the research, the evaluation report includes the results for interested parties.

3.2 Summary of CO_2 Laboratory Testing Results

The primary goal of laboratory testing was to establish that the test conditions described in the draft could be achieved. This included the required range of temperature and relative humidity targets, along with the required CO_2 concentrations, within all the allowed tolerances as described in the test method. For the CO_2 test method, all these targets and tolerances are expected to be published in a finalized ASTM test method.

For a full and detailed report, the results are published in AQ-SPEC's laboratory report Evaluation Report for Four CO_2 Sensor systems Following the draft Standard Test Method for Evaluating CO_2 Indoor Air Quality Sensors or Sensor Systems Used in Indoor Applications (ASTM D22.05) (Kuang, Mui, and Papapostolou 2020). In addition, ASTM will publish an intra-laboratory study to establish a repeatability statement for the finalized test method if approved.

The ASTM document will summarize the precision and bias of the method as demonstrated by single laboratory testing. Because these test results are or are expected to be published by ASTM, highlights of the testing are discussed here.

3.2.1 Tolerances

The chamber was able to reach steady-state CO_2 targets within +/-3% RSD, a tighter tolerance than what was achievable in generating $PM_{2.5}$ concentrations. In addition, an absolute tolerance of +/-3% or +/-10% was added, similar to what was established in the $PM_{2.5}$ test approach, to ensure that steady state was achieved at a concentration close to that of the target. The broader absolute tolerances were needed at lower CO_2 concentrations, where concentrations varied more relative to the target. In the test method, users are directed regarding which concentrations much meet which specific tolerances.

3.2.2 Phase 1: Concentration Ramping Results

During the initial concentration ramping test, low-cost CO_2 sensors performed well and tracked reference monitor concentrations with a Pearson linear coefficient of determination correlation >0.99. According to the AQ-SPEC evaluation report, "all test sensor systems showed low bias and strong correlations with the CO_2 reference monitor during Phase 1 testing" (Kuang, Mui, and Papapostolou 2020). Although the performance of the test sensors is not part of the research, the evaluation report includes the results for interested parties.

3.2.3 Phase 2: Effects of Temperature and Relative Humidity

Phase 2 testing was adjusted in the same manner as the $PM_{2.5}$ testing. The same physical limitations of the chamber regarding extreme temperature and relative humidity levels, as well as practical concerns of limiting test time, were also experienced during CO_2 testing. For this reason, temperature targets were reduced from six to three to reduce testing time. The draft included testing at 15°C, 20°C, 30°C, 40°C, 50°C, and 60°C. The final test method included only 20°C, 30°C, and 50°C. Although fewer combinations were used, this still represents a likely range of common indoor conditions that a sensor might experience. Likewise, relative humidity targets were reduced from five to three to reduce test time and because the test chamber was unable to reliably reach relative humidity of 90% or higher. The draft included targets at 15%, 40%, 60%, 75%, and 90% relative humidity. The final test method only included 40%, 60%, and 80% relative humidity.

Finally, the pollutant concentrations that were tested for each temperature, and relative humidity combinations were reduced from three to two to reduce testing time. The draft included concentrations at 1,000, 2,000, and 5,000 ppm, while the post-testing draft included only 1,000 and 5,000 ppm. The effect on the test method was a decrease in necessary test time by weeks.

According to the AQ-SPEC evaluation report, "the results from the effect of temperature and relative humidity testing in Phase 2 showed that impact of temperature was not as clear and consistent as that from [relative humidity]; in most cases the test sensor systems showed higher magnitudes of mean error values at the highest [relative humidity] tested" (Kuang, Mui, and Papapostolou 2020) Although the performance of the test sensors is not part of the research, the evaluation report includes the results for interested parties.

3.2.4 Phase 3: Relative Humidity Interferent Testing

Low-cost CO_2 sensors tested performed well in relation to relative humidity as an interferent, especially in conditions commonly experienced in the home. According to the AQ-SPEC evaluation report, "Phase 3 interferent study results showed that [relative humidity] had little influence as an interferent on the reported CO_2 concentrations from test sensor systems at conditions of 60% [relative humidity] and lower; while the test sensor systems reported higher CO_2 concentrations at greater [relative humidity] conditions, these findings cannot be interpreted in this study because the CO_2 concentration could not be held at 1,000 ppm during these higher [relative humidity] conditions." (Kuang, Mui, and Papapostolou 2020) Although the performance of the test sensors is not part of the research, the evaluation report includes the results for interested parties.

3.2.5 Phase: 4 Temperature Cycling

No data are collected during Phase 4. All sensors remained operational during the phase (Kuang, Mui, and Papapostolou 2020). Although the performance of the test sensors is not part of the research, the evaluation report includes the results for interested parties.

3.2.6 Phase 5: Final Concentration Ramping

Phase 5 testing repeats Phase 1 concentration ramping with the goal of measuring drift after artificially aging the sensors 1 year during Phase 4 of the testing. According to the AQ-SPEC's evaluation, "the Phase 5 results indicated that the difference between the reported CO_2 measurements in Phase 5 and Phase 1 was generally minor at lower CO_2 test concentrations and the differences increased at higher CO_2 test concentrations for all, but one sensor model tested." Like the PM2.5 testing, the drift encountered in the low-cost sensors was more pronounced at higher concentrations (Kuang, Mui, and Papapostolou 2020). Figure 11 depicts average drift across the four sensor models, showing the tendency for several models to underestimate ppm after a simulated year of use. Although the performance of the test sensors is not part of the research, the evaluation report includes the results for interested parties.

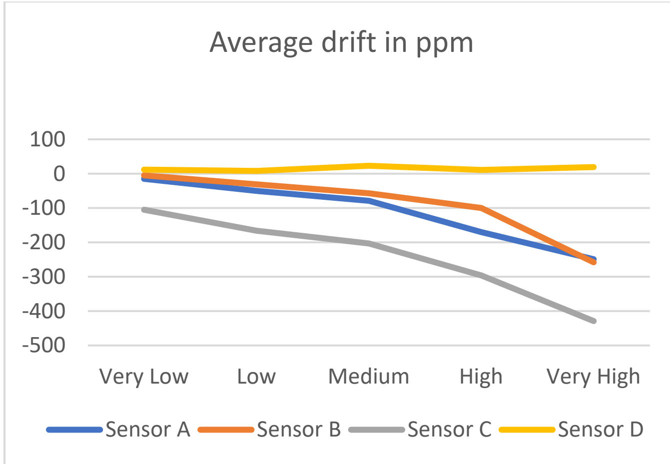

Figure 11. Average drift across four sensor models

Source: Kuang, Mui, and Papapostolou 2020

3.3 ASTM Approval and Publication of $PM_{2.5}$ Test Method

3.3.1 First Ballot

The draft test method was first submitted for ballot on February 28, 2020, and ballots closed March 30, 2020. The first draft of the ballot was well-received by the D22.05 Subcommittee, with 82.6% affirmative ballots. Although this is enough of a margin to pass the item at the subcommittee level, the ASTM process requires attempts to address any negative comments. Eight commenters submitted negative ballots, many with multiple suggestions, totaling 161 comments, suggestions, or clarifying questions.

3.3.2 Second Ballot

The draft was submitted for a second ballot on September 15, 2020, and closed October 16, 2020. The second ballot received an even more favorable response than the first ballot, with 91.83% affirmative ballots. While two subcommittee members submitted affirmative ballots with comments, only six subcommittee members submitted negative ballots. The total number of negative comments was reduced from 161 on the first ballot to 23 on the second ballot, with the majority being small editorial changes or clarification questions.

3.3.3 Third Ballot

The draft test method was submitted for third ballot on March 22, 2021, and ballots closed April 21, 2021. The ballot received 95.34% positive ballots from the D22.05 Subcommittee. Only two ballots were returned negative, with a total of four comments, all of which were minor.

3.3.4 Concurrent Ballot

A concurrent ballot is sometimes used when only minor negative comments are received at the subcommittee level, and these comments were resolved to the satisfaction of the commenters with only minor edits. Both the D22.05 Subcommittee chair and D22 Committee chair agreed that the test method could be brought forward to the full committee as a Concurrent Ballot. This means that both the subcommittee and full committee vote at the same time. On June 30, 2021, the $PM_{2.5}$ test method was submitted for concurrent ballot. No negative ballots were received, and the item was approved for publication.

3.3.5 Editorial Review and Publication

ASTM staff perform an editorial review of the test method, as well as performing final publication formatting on the document. *ASTM D8405-21 Standard Test Method for Evaluating* $PM_{2.5}$ *Sensors or Sensor Systems Used in Indoor Air Applications* was officially published by ASTM in September 2021. This standard is now fully approved, published, and available for use. It is also referenceable as a consensus standard for any organization that wants to reference the test method in requirements related to indoor air quality sensors.

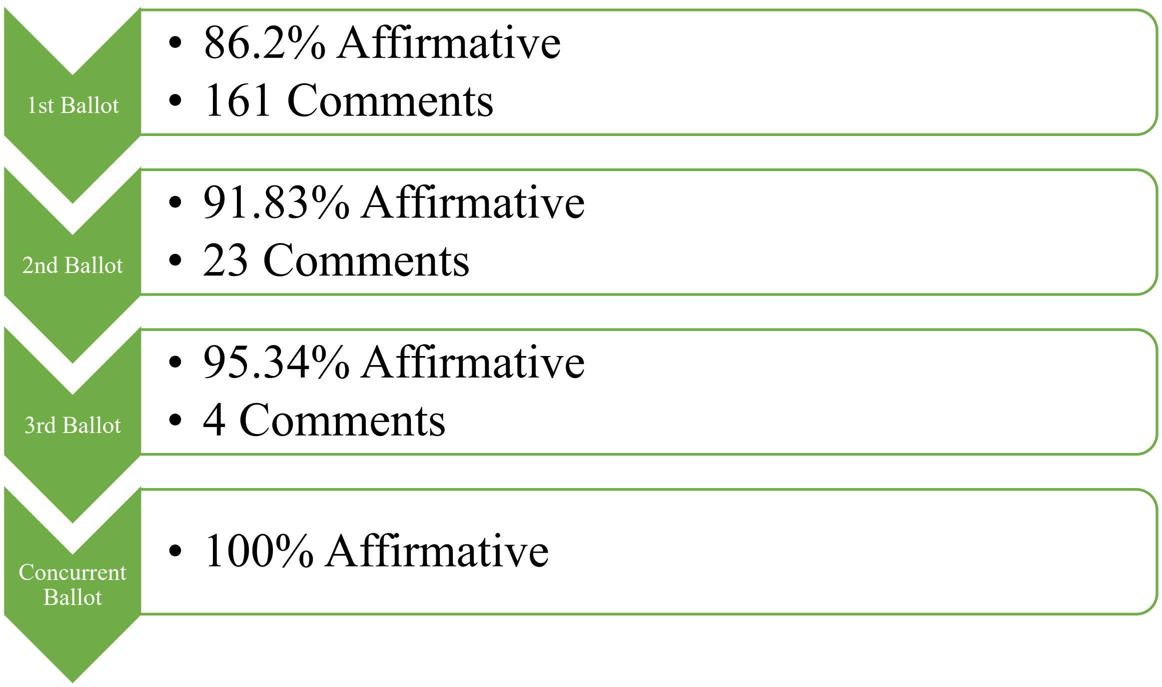

Figure 12. Summary of $PM_{2.5}$ test method ballot results

3.4 ASTM CO_2 Test Method Progress

3.4.1 First Ballot

The draft CO_2 test method was first submitted for ballot on December 17, 2021. Ballots closed January 17, 2022. The first ballot was well-received by the D22.05 Subcommittee's 90.47% affirmative ballots—8% higher than the 82.6% affirmative votes received by the first draft of the $PM_{2.5}$ test method. Five subcommittee members submitted negative ballots with 72 comments (including a few comments from affirmative ballots). This is a 55% reduction in comments compared to the first $PM_{2.5}$ ballot. Most of the comments were editorial or minor clarifications, while a few dealt with continued discussion of the effects of pressure on CO_2 sensors and how to adequately capture that in the test method.

3.4.2 Second Ballot

Because many of the comments, while minor, were persuasive, a second ballot was necessary to approve the standard at the subcommittee level. At the time of this report, the CO_2 test method draft is being prepared for a third ballot.

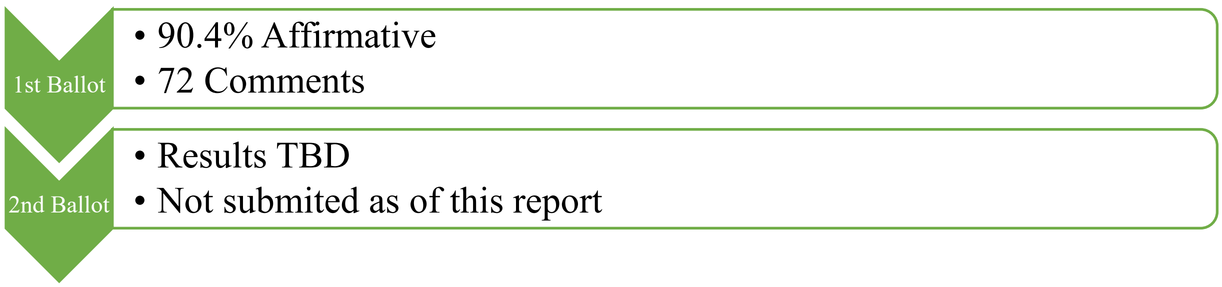

Figure 13. Summary of CO_2 test method ballot results

4 Discussion

4.1 Major $PM_{2.5}$ Technical Issues and Solutions

4.1.1 Performance Description of Test Conditions

The test conditions were described, whenever possible, on a performance basis, rather than a prescriptive one. This meant that rather than requiring exact specifications such as chamber dimension or fan speed, the test method set limits on specifications, when appropriate, but otherwise allowed flexibility for different laboratories to achieve the test conditions. One laboratory might have a chamber that is larger than another and would need to adjust their pollutant delivery and fan system to meet the required test conditions.

4.1.1.1 Steady-State Conditions

All pollutant measurements in the test method are taken at steady-state conditions. This is achieved in the test when the reference monitor reaches the pollutant concentration targets within a prescribed percent relative standard deviation limit (tolerances vary based on pollutant and concentration) over 20 consecutive measurements. A minimum of 20 measurements at each test point are compared. The time this will take varies by the chamber and the time resolution of the reference monitor and test sensor. The 20 measurements are based on the longer of the time resolution of the test sensor and the reference monitor. The reference monitor is required to have a time resolution of 1 minute or less, so measurements at steady state will take at least 20 minutes to measure. However, if the test sensor had a time resolution of 2 minutes, this time would double to record 20 measurements. The target concentration must be reached within the absolute tolerance and relative standard deviation tolerances stated in the test method. In this way, the chamber is confirmed to reach a pollutant concentration, by the reference monitor, without deviating beyond the tolerances allowed.

To be able to maintain steady-state conditions, most chamber systems will need to introduce pollutant into the chamber constantly while operating the system under positive pressure, rather than a one-time introduction of pollutant at a specific pressure. By basing steady state on relative standard deviation, the test relies on the reference monitor to establish what the pollutant concentration should be in the chamber system. Test sensor readings are only compared during the reference monitor steady-state period. Other test approaches, such as a field test (in homes or office spaces), would need to accept whatever pollutant concentration the reference instrument experiences but would not be able to repeat concentration tests with any precision.

4.1.1.2 Homogeneity

Homogeneity is established in the standard by requiring steady-state measurements that do not vary by more than a tolerance of +/- 2% at the location of the reference monitor sampling probe and the location of the test sensors. In all tests, test sensors are evaluated in triplicate, at a minimum. It is possible that an experiment could be performed with more than three sensors for any model, if desired. It is also possible that multiple models (each in triplicate) could be tested at once if the chamber could accommodate that number of sensors and if homogeneity could be achieved. The ability to achieve homogeneity is something that would need to be tested and verified during chamber setup because it cannot be tested during a sensor test without multiple reference probes. Having a chamber that can produce the required test conditions will take time and experimentation for each laboratory that develops a chamber system, as each system may be slightly different unless built as an exact replica of an existing system. This approach also ensures that test sensors will experience the same conditions as the reference monitor. If a different approach had been taken in the test method, and a specific fan speed was required for mixing, it might be possible for sensors in one chamber to experience conditions differently than in another chamber system. Likewise, not using a chamber but exposing sensors to cooking pollutants in a living space will not ensure homogeneity. By using performance criteria, the method can fix test conditions across all experiments.

4.1.2 Applicable Sensors and Sensor Systems

Early in the development process, significant discussion centered around what types of sensors the test would be applicable to. For example, there are many devices that include multiple raw sensors linked together in a package that has feedback/communications capability. Because the test method compares test sensor data to a reference monitor, the test is limited to test sensors with a means of power that can operate the device throughout the test (either line or battery). In addition, the sensors must be able to record/communicate the data. Therefore, a raw sensor with these minimal capabilities could be tested, while a raw sensor without power or ability to communicate data would not be able to be tested. Sensor systems with multiple integrated raw sensors were also able to be tested (e.g., a consumer air quality monitor with multiple sensors packaged in a unit). This was an important point because many consumer devices fit into the sensor system category. The test method references sensors or sensor systems for this reason.

The TAG also discussed whether to use the test for air quality sensors in any location or only sensors intended for indoor use. The test method eventually incorporated sensors only intended for indoor use. There is a separate standard meant to test sensors intended for ambient/outdoor use being developed within the ASTM D22 Committee.

Finally, there was significant debate about how to define low-cost for the purposes of this test method. While the project was intended for low-cost sensors, there was no specific reason to place a price cap on the test method. Prices are likely to change over time and a specific cap might lose its relevance before the next revision of the standard. The final decision was not to limit the applicability of sensors by cost.

4.1.3 Particle Source

Significant debate during development of the test method within the TAG, as well as within the ASTM D22.05 Subcommittee, concerned the aerosol chosen to represent $PM_{2.5}$, as well as interferent particles (coarse particles up to PM_{10} in size). This debate stems from several issues. First, there is no industry consensus on one representative aerosol for use in representing PM in laboratory tests. Next, indoor aerosols and outdoor aerosols can vary significantly with organic aerosol sources commonly encountered indoors. However, finding organic aerosol sources that are standard reference materials, which can also be easily compared to similar interferent aerosols from other standard reference materials, was not possible. The priorities for particle source were:

- Aerosols that are easily accessible reference materials
- Aerosols that represent indoor $PM_{2.5}$
- Aerosols that are easy to compare with larger interferent particles.

4.1.3.1 Whether to Specify a Specific Aerosol

The issue of whether to require a specific test aerosol and/or interferent aerosol was discussed during the development of the draft test method. In the initial draft submitted to ASTM, the project team chose to allow multiple test aerosol and interferent aerosol options with the goal of allowing more flexibility across multiple laboratories to achieve the test conditions required. This decision was primarily driven by the fact that there was no broad consensus on any one appropriate aerosol, and the project team wanted to avoid battles among different groups recommending different specific aerosols.

Comments from the first ballot, however, focused heavily on specifying a required test aerosol and interferent aerosol. Commenters argued that without a specific test aerosol prescribed by the test method, it would be impossible to completely characterize the precision and bias of the test method or adequately identify possible bias. If one laboratory used NaCl to generate $PM_{2.5}$ while another laboratory used ammonia sulfate ($(NH_4)_2SO_4$) and a third laboratory used polystyrene latex (PSL) spheres, the data coming from these experiments might vary significantly and would characterize the performance of sensors being tested differently.

The project team found these arguments persuasive and prescribed NaCl initially as a response. A secondary test with PSL spheres was later added due to discussions with the subcommittee. That decision is described in Section 4.1.3.3.

4.1.3.2 Comparable Test Aerosols and Interferent Aerosols

Selection of a specific aerosol to be used during testing was partially driven by the ability to find comparable aerosols to use during the interferent phase of testing. For interferents, the test method uses larger particles up to PM_{10} to test sensors. To be able to run the interferent test, it was important to use an interferent aerosol with a similar refractive index to that of the test aerosol for repeatability of results. This factor made the choice of NaCl the best choice for a test aerosol because it has a similar refractive index to that of Arizona Test Dust, the source chosen for the interferent particle. Table 4, developed during ASTM consensus discussions, shows analysis performed by South Coast AQMD to identify the ideal test aerosol/interferent aerosol combination (Papapostolou and Mui 2021).

Table 4. Aerosol Source Selection Considerations

Material	Refractive Index	Density g/cm^3	Deliquescence Relative Humidity	Comments
Chosen PM_c Material				
Arizona Test Dust ISO12103-1 Grade A4 Coarse	1.54	2.65	N/A	Chosen coarse PM material for test standard Established use in aerosol community Standardized size distributions (< ~5% of mass from particles smaller than ~2.5 um)
Candidate $PM_{2.5}$ Materials				
Polystyrene Latex (PSL)	1.6	1.05	N/A	Expensive Cannot be used for RH tests
Sodium Chloride (NaCl)	1.54	2.16	75%	Chosen fine PM material for test standard Refractive index closely matches coarse PM material. Density is the closest to coarse PM material, and reference monitor readings can be adjusted to account for this difference. Widely available Inexpensive DRH falls within the RH range for Phase 2 testing.
Ammonium Sulfate ($(NH_4)_2SO_4$)	1.521	1.77	80%	DRH already at upper bound of RH range for Phase 2 testing.
Ammonium Bisulfate (NH_4HSO_4)	1.473	1.78	40%	DRH already at lower bound of RH range for Phase 2 testing.

Material	Refractive Index	Density g/cm^3	Deliquescence Relative Humidity	Comments
Potassium Chloride (KCl)	1.49	1.98	84%	This material was used in SC AQMD's execution of the test method. Phase 1 experimental work had already been completed by the time that Phase 2 RH > 80% could not be realized, or that Phase 3 refractive index was slightly different than only suitable PM_c material; however, these do not affect the method itself.
Sulfuric Acid (H_2SO_4)	1.426	1.83	Continuous water uptake	Poses significant risks for users and equipment

*Table Developed by South Coast AQMD AQ-SPEC staff (Mui and Papapostolou).

4.1.3.3 Inorganic Aerosols Versus Organic Aerosols

The debate over whether to use organic or inorganic aerosol sources for the test method represents one of the largest barriers to testing indoor air quality sensors. Many of the $PM_{2.5}$ sources in the indoor environment are organic. However, the best choices for standard reference materials to use in laboratory testing are inorganic. Organic aerosols may behave differently, and therefore interact with sensors differently than inorganic aerosols.

Initially, the test method allowed multiple options for test aerosols. However, as identified in Section 4.1.3.1 the project team eventually decided on NaCl to provide a higher level of accuracy and repeatability of the test method from laboratory to laboratory. This aerosol source was chosen because it was standard reference material that could be easily found by laboratories. In addition, as mentioned in Section 4.1.3.2, NaCl was chosen because it had a similar refractive index to Arizona Test Dust, which would be used as an interferent particle in Phase 3 of the test.

This raised an issue with the test method because NaCl is inorganic, while likely indoor particles encountered in a real environment would be more often organic. Concerns were raised by the committee over whether the results would adequately assess a sensor's real-world performance. Throughout the development process, at the TAG as well as the ASTM subcommittee, this issue was discussed. It presented a problem without a solution because a laboratory test needs to be repeatable, and no organic aerosol could be identified that was a standard reference material that would give consistent results. Likewise, there is no single organic aerosol that would represent all organic aerosols in its behavior.

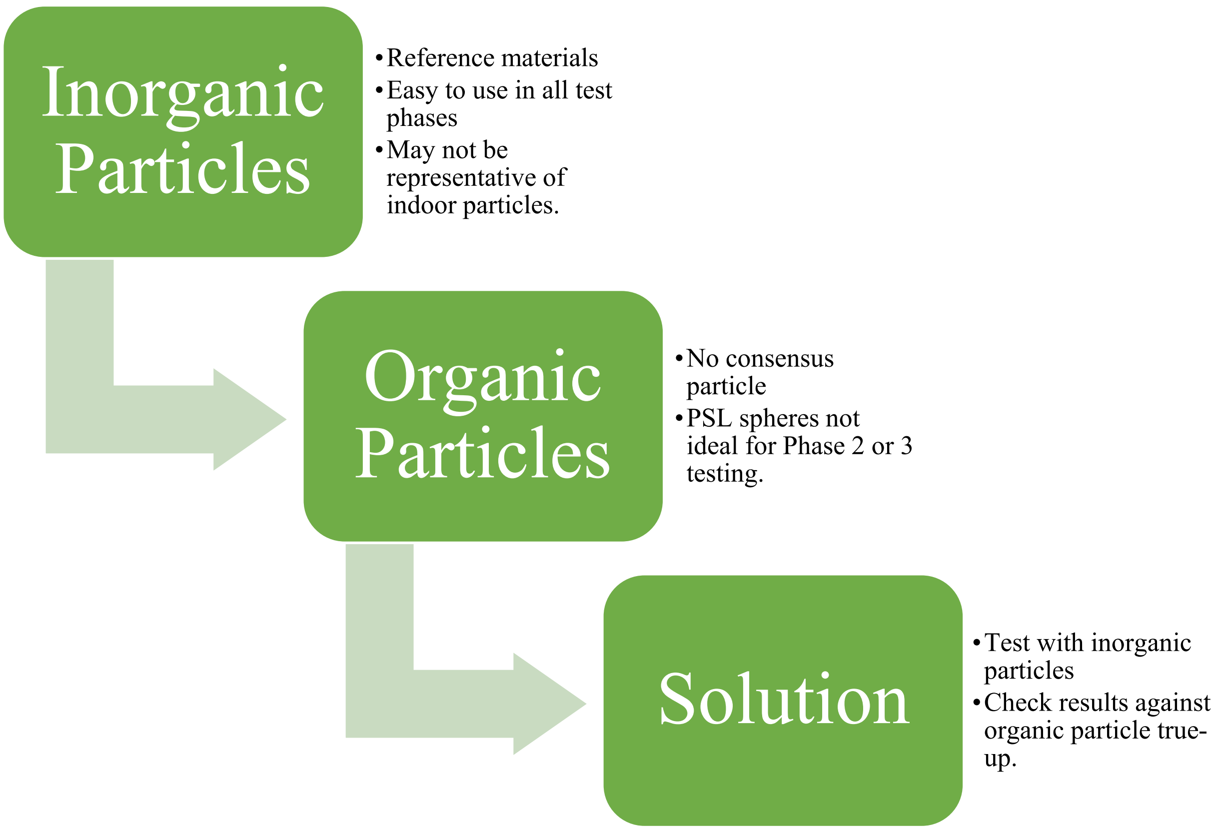

Figure 14. Particle source: inorganic versus organic

The only organic aerosol identified as a standard reference material that could act as a test aerosol were PSL spheres. The problem with using PSL spheres as the primary test aerosol is that the ability to test high relative humidity conditions is limited due to its hygroscopic properties. In addition, PSL spheres were not practical for use as the interferent aerosol because it was not possible to generate high volumes of PSL spheres at larger particle sizes.

In discussions with the subcommittee, it was proposed to do a "true-up" test with PSL spheres as a way of providing a check on the results of the test that would primarily use NaCl as the test aerosol. Phase 1 concentration ramping will therefore be run twice—once with inorganic $PM_{2.5}$ and once with organic $PM_{2.5}$—so that results of the test can be interpreted understanding the different responses of the test sensors between organic and inorganic $PM_{2.5}$. Phases 2, 3, and 5 tests are conducted with inorganic $PM_{2.5}$.

4.1.4 Reference Monitors

As a regulated pollutant, there were multiple reference monitor options that could be considered for the $PM_{2.5}$ test method. FRM monitors represent the best available technology for sampling $PM_{2.5}$, use a gravimetric measurement, and are subjected to rigorous testing ensuring their accuracy. However, the measurements taken using an FRM take multiple hours, making their use impractical for a chamber test. FEM monitors are also subjected to rigorous testing but have much shorter time resolutions for their measurements. The test method allows an FEM Class III monitor and requires reference monitors that have a time resolution of 1 minute or less. This means that they will record a measurement at increments no greater than 1 minute. At steady-state conditions, it would be possible to take 20 steady-state measurements in 20 minutes if the test sensor also had a time resolution of 1 minute.

The issue of choosing a reference monitor specification was an example where ASTM subcommittee members provided comments suggesting opposing approaches, and consensus needed to be reached. Several members suggested that Asian or European standards be allowed for reference monitor specifications, to make the test method more accessible internationally. Other subcommittee members argued that without an FEM or FRM designation, there would be no way to understand the precision and bias of the test method. FRM and FEM monitors have already been subjected to precision and bias testing, and therefore their abilities are able to be quantified. Still, other subcommittee members expressed concern regarding requiring FRM or FEM monitors because it might not be practical to use a reference monitor of that sophistication to test sensors of other substances, such as formaldehyde or CO_2. As a non-regulated substance, CO_2 does not have FRM or FEM designations for monitors, so best available technology would need to be referenced.

Consensus was reached in the subcommittee through negotiations with multiple parties that an FRM or FEM designation was needed for the purpose of precision and bias. FEM was selected due to the shorter time resolution. It was acknowledged that other test methods may not be able to use FEM reference monitors. In these cases, best available technology would need to be defined or specified by the test method.

Reference monitors receive their designation according to *CFR 40 Part 53*. It is important to note that the reference monitors used here carry the FEM designation that is only valid in outdoor applications for FR sampling and measuring ambient air. The designation is used here to distinguish between monitors carrying that designation for outdoor applications and those that do not have the designation for outdoor applications, making the "FEM" monitors "extra reliable" overall. The actual use of the monitors in these tests is not described/supported by the FEM designation.

4.1.5 Gravimetric Measurements

Even using sophisticated measurement equipment like a Class III FEM monitor as a reference monitor, there was concern that the test method needed additional checks to ensure that the reference monitor was accurately measuring pollutant concentrations in the test chamber. FEM monitors are primarily designed and tested for monitoring ambient air conditions. Several subcommittee members expressed concern that the FEM monitor may not perform as well in a chamber environment. Likewise, the test method was using inorganic particles for testing, but was also using organic particles (see Section 4.1.3.3 for further discussion), and it was unclear how FEM monitors would perform while measuring organic particles.

For this reason, a gravimetric check was developed to be performed before Phase 1 of each sensor test. This would not be a full gravimetric calibration but might result in such a calibration if the reference monitor performed outside of allowable tolerances. This gravimetric check satisfied all concerns about the accuracy of the FEM monitor as a reference monitor during the test. During an ASTM D22.05 Subcommittee meeting, one member described the rigor represented by the gravimetric test as the "gold standard" in sensor testing.

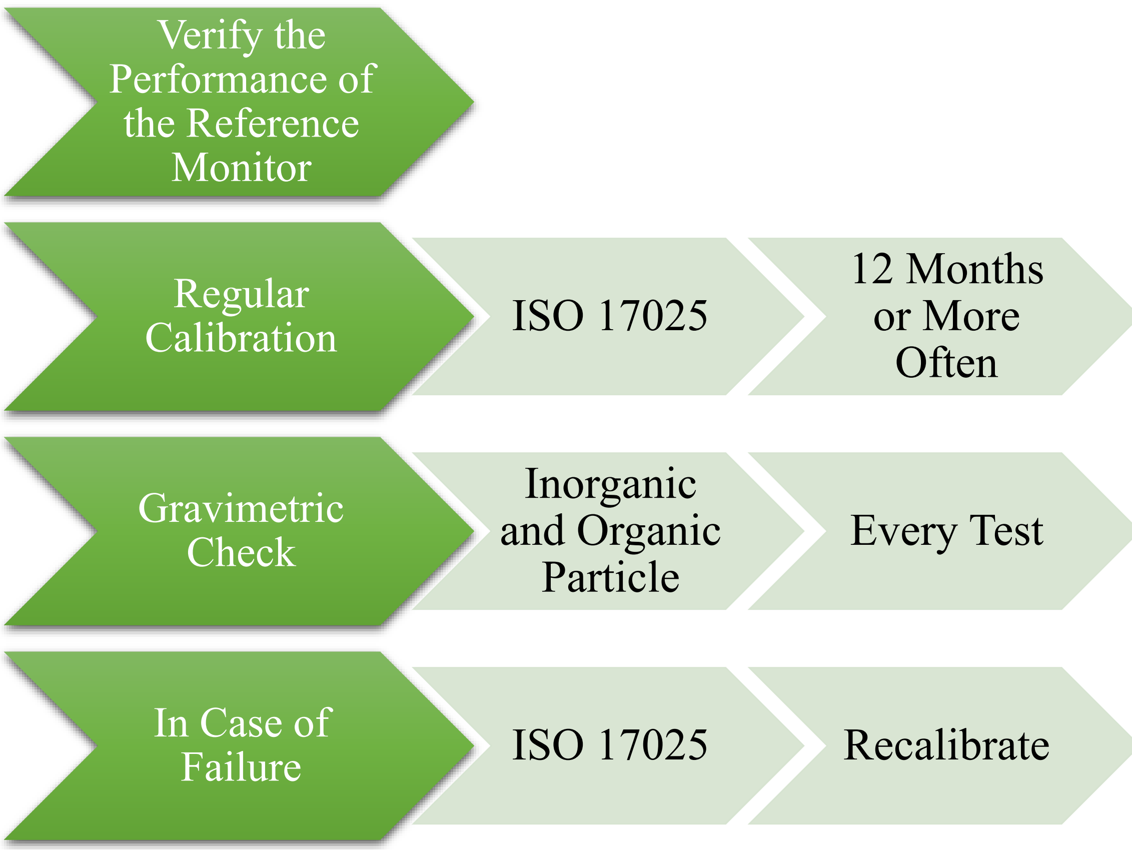

Figure 15. Verifying the performance of the reference monitor

4.1.6 Accelerated Aging and Drift

One important goal of the test method is to know how sensors and sensor systems will perform over time. A new sensor may be accurate and respond well to the presence of pollutants but lose accuracy over time. To measure the drift of sensors over time, a method of aging the sensors was needed.

One possible approach would be to test sensors, deploy them in the field, and then test them again. Newport ultimately decided against this approach due to feasibility. A manufacturer would not agree to have their system deployed by an end user and then retested because they would have no control over the end user and any damage that might be done outside of actual use. In addition, sensor models are updated frequently and there is not enough time to wait a year or more to get results from prolonged field testing. No manufacturer would be able to wait that long for finalization of their test results.

Another approach would be to artificially age sensors by subjecting them to an extreme event of $PM_{2.5}$ exposure. Newport also decided against this approach based on advice from South Coast AQMD's AQ-SPEC staff. The chamber, reference instruments, and other equipment being exposed to extreme pollutant events could rapidly degrade, causing costly repair and replacement of the laboratory chamber system, and making the test method cost-prohibitive.

The final selected approach was to mimic one year of mechanical stress by using a temperature cycling procedure developed by a sensor manufacturer and introduced during the TAG process. The mechanical stress of changes in temperature will naturally age the sensor. This process was based on the Coffin-Manson Model (Coffin 1954; Rueffer 2019), which speeds up the aging process by expanding the typical temperature cycle range that a sensor would experience in a day. In this way, the test method achieves the equivalent of a year's worth of mechanical stress within a matter of hours. The exact time depends on how quickly the chamber system can complete a full temperature cycle.

4.1.7 $PM_{2.5}$ Concentrations and Temperature/Relative Humidity Combinations

The $PM_{2.5}$ test method was approved with six concentrations, including one concentration at the lower limit of detection of the reference monitor and five other concentrations ranging from 10 micrograms per cubic meter ($\mu g/m^3$) to 300 $\mu g/m^3$. These concentrations are tested during Phase 1 (concentration ramping) and Phase 5 (drift) of the test method while the chamber environment is held at 20°C and 40% relative humidity. As mentioned in the discussion of accelerated aging, 300 $\mu g/m^3$ was the highest limit of $PM_{2.5}$ that laboratory staff were comfortable subjecting the test equipment to without risk of damaging the chamber system.

Temperature and relative humidity targets were selected to represent the range of conditions that might be experienced indoors. During Phase 2 (effect of temperature and relative humidity), sensors are tested at both 10 $\mu g/m^3$ and 50 $\mu g/m^3$ while temperature ranges from 20°C to 50°C and 40% to 80% relative humidity. The initial draft test method started with 8 temperatures, 5 relative humidity levels, and 3 pollutant concentrations for a total of 120 combinations. All combinations needed to be run for at least 20 measurements of the reference monitor at steady state, meaning at least 40 hours of testing if the reference monitor had a time resolution of 1 minute, not counting the time bringing the chamber to steady state or changing temperatures.

In practice, this phase would have taken months to complete for the laboratory doing initial testing. To make the test practical, the combinations were reduced to 3 temperatures and 3 relative humidity targets with 2 pollutant concentrations for a total of 18 combinations. Still, producing a robust data set of 360 data points, this modified phase was much more reasonable to complete. In addition to reducing the number of combinations, the modified targets also eliminated extreme temperature and relative humidity targets that were difficult to achieve in the chamber and were outside of typical indoor conditions that would be experienced by sensors.

During Phase 3 (particle size interferent testing), sensors are subjected to coarse particles of PM_{10} in four concentrations ranging from 10 µg/m^3 to 150 µg/m^3, while $PM_{2.5}$ concentrations are held to 50% or less of the total particle concentration in the chamber. Phase 4 does not collect data. For more detailed descriptions of specific concentrations and test chamber environment targets, see *ASTM D8405-21*.

4.1.8 Minimum Test Time

A concern during the development of the test method was establishing a minimum amount of test time. Because the test method is written so that there can be some variability in chamber systems, if the test conditions can be generated, there will be variation in how long it will take to complete the test. The test method includes a minimum test time of 15 days for this reason in case a chamber system is developed that could quickly complete the test but would not have exposed the test sensors to enough testing. During the development process, a testing minimum was thought to be necessary in case some possible deficiencies appeared that would not appear during a shorter time period. This is especially important if sensors have any type of autocalibration function. See the following CO_2 section for further discussion of this issue with CO_2 sensors. With current chamber system performance, demonstration of the test method took weeks, rather than days, and significantly surpassed the 15-day minimum.

4.2 Major CO_2 Technical Issues and Solutions

4.2.1 Performance Descriptions of Test Conditions

This issue is described above in the $PM_{2.5}$ section. No further CO_2-specific nuance is added, but the description above is applicable.

4.2.2 Applicable Sensors and Sensor Systems

This issue is described above in the $PM_{2.5}$ section. No further CO_2-specific nuance is added, but the description above is applicable.

4.2.3 CO_2 Delivery and Reference Materials

Two options are allowed in the draft CO_2 test method for delivering CO_2 into the test chamber. Originally, the draft only had one method in which CO_2 from a certified cylinder was mixed with dilution air to achieve the desired CO_2 levels. During discussions with stakeholders, there was a request that laboratories be able to deliver CO_2 directly to the chamber without dilution air in specific amounts. If the steady-state test conditions can be met, either approach is acceptable. There was significant debate on how to describe reference materials.

The test method references *International Organization for Standardization (ISO) Guide 30* or the National Metrology Institute of the Netherlands Primary Reference Materials to define both Certified Reference Materials and Reference Materials. Calibration of equipment is required to be conducted with Certified Reference Materials. Likewise, Reference Monitors and certified CO_2 cylinders are required to be traceable to Certified Reference Materials. Testing itself may be performed with Reference Materials instead of Certified Reference Materials to reduce costs.

4.2.4 CO_2 Scrubbing and Baseline Measurements

Beginning a sensor test with the chamber environment at 0 PPM of CO_2, which would have allowed testing sensors at the lower limit of detection of the reference monitor, was impractical due to cost reasons. Due to the naturally high levels of CO_2 in indoor and outdoor air, scrubbing of CO_2 from the chamber environment would have required large amounts of scrubbing material and would have been cost-prohibitive for any laboratory to complete. For this reason, the baseline measurement was initially set at 400 PPM. However, in conducting the laboratory experiment, the lowest baseline level the laboratory was able to reliably reproduce in the chamber environment was 450 PPM, which was therefore set as the baseline measurement for the test method.

4.2.5 Reference Monitors

A major challenge to developing a test method for low-cost CO_2 sensors is that there are no CO_2 sensors with an FRM or FEM designation because CO_2 is not a regulated pollutant in the same way that PM2.5, NO_2, or O_3 would be, for example. For this reason, the best available technology must be used as a reference material instead. Research-grade CO_2 sensors are available that can serve as reference monitors, and the test method describes the capabilities that these sensors must possess including time resolution, accuracy, and range of CO_2 detection. The reference monitor is validated with a multipoint calibration using a CO_2 cylinder meeting the Certified Reference Material requirements defined in the test method. "The CO_2 reference monitor used in this test method was a Thermo Scientific 410iQ Carbon Dioxide Analyzer. This instrument uses advanced non-dispersive infrared optical filter technology to measure CO_2 concentrations up to a concentration of 10,000 ppm. This CO_2 reference monitor had a detection limit of 1 ppm CO_2" (Kuang, Mui, and Papapostolou 2020).

4.2.6 Accelerated Aging and Drift

This issue is described in the $PM_{2.5}$ section. No further CO_2-specific nuance is added, but the description above is applicable.

4.2.7 Appropriate CO_2 Concentrations and Temperature/Relative Humidity Combinations

The same conditions that drove the limitation of temperature and relative humidity combinations in the $PM_{2.5}$ test method also presented problems for the CO_2 test method. As a result, the same adjustment to temperature and relative humidity combinations was implemented in the CO_2 test method. No further CO_2-specific nuance is added, but the description above is applicable.

4.2.8 Automatic Calibration and Minimum Test Time

In addition to the discussion of minimum test time introduced in the $PM_{2.5}$ section above, the minimum test time is especially important for CO_2 sensors and sensor systems because many low-cost CO_2 sensors and sensor systems include an integrated automatic calibration. In general, the automatic calibration uses the lowest average reading over a certain amount of time, and automatically recalibrates the sensor to have this reading equal a set baseline. For example (summary of example shown in Figure 16), if the autocalibration is set to occur over 7 days of use and the set baseline is 700 PPM, a sensor that experiences 600 PPM of CO_2 as its lowest average concentration over those 7 days will recalibrate 600 PPM as 700 PPM. This means that over the next 7-day period, the CO_2 sensor would overestimate the concentration of CO_2 by 100 PPM. If the sensor continues to experience the same levels of CO_2 over multiple calibration periods, the high estimation will become more pronounced.

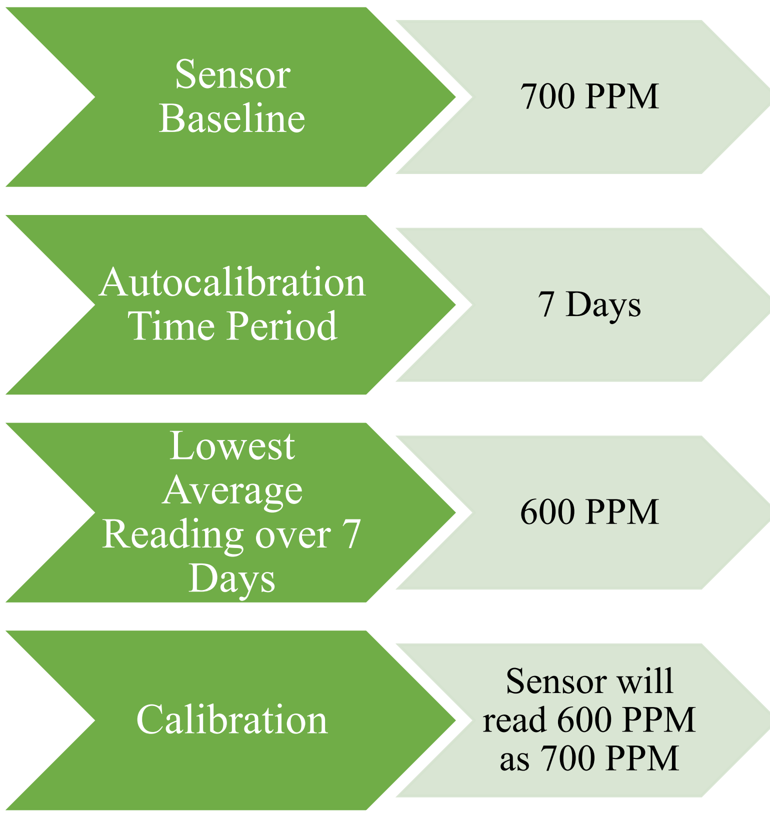

Figure 16. Possible autocalibration scenario

To evaluate the effect of this autocalibration feature during the test method, it is necessary that the testing would occur for longer than one calibration period. The minimum 15-day testing period (which will likely be longer in practice) ensures that any inaccuracy due to the autocalibration will show up in the test data if the calibration feature is less than the test period.

Autocalibration periods that are longer than the testing cannot be characterized. However, variation in autocalibration periods make it impossible to definitively cover all sensors. For sensors that possess autocalibration functionality, the test method requires that that functionality be activated for the test.

4.2.9 Atmospheric Pressure

The TAG and the ASTM subcommittee discussed the effects of atmospheric pressure on CO_2 sensors. The issue is that atmospheric pressure can affect the accuracy of CO_2 sensors, especially nondispersive infrared sensors. In addition, some manufacturers have automatic features to adjust for the effects of atmospheric pressure. Including any kind of pressure adjustment factors in the test method proved impractical for many reasons.

A laboratory could perform the testing at one location at local atmospheric pressure, while the sensor was manufactured at a different location with different local atmospheric pressure. Likewise, the final product will possibly be used at a location with a completely different atmospheric pressure. Experts from the TAG and the ASTM D22.05 Subcommittee were unable to identify any tested consensus approach for accounting for these differences.

Because there was no tested approach, the test method could not include atmospheric pressure effects as part of the evaluation. However, an informative (non-mandatory) appendix discussing how a laboratory could study pressure effects was included based on initial research from one ASTM subcommittee member. While the author of the appendix admits that it was not ready for mandatory inclusion, the hope is that by the time the standard is updated, a consensus approach to evaluating pressure effects could be included in the full standard as a mandatory part of the test.

4.3 Significance of the Test Methods

4.3.1 Test Method for IAQ Sensors

This project resulted in the first-of-its-kind publication of a standard test method for IAQ sensors. *ASTM D8405-21* was the first consensus test method that specifically covered laboratory testing of sensors intended for indoor use. Other test procedures existed that were intended for ambient (outdoor) air sensors, mainly because the sensors were intended for tracking air pollution rather than for evaluating indoor environments.

This standard is precedent setting as an example for the future development of other similar IAQ sensor test methods. In addition, it is the first step in evaluating the performance of low-cost IAQ sensors, beginning the process of introducing reliable low-cost IAQ monitoring to the market.

4.3.2 Technical Support Catalyst for Standard Development

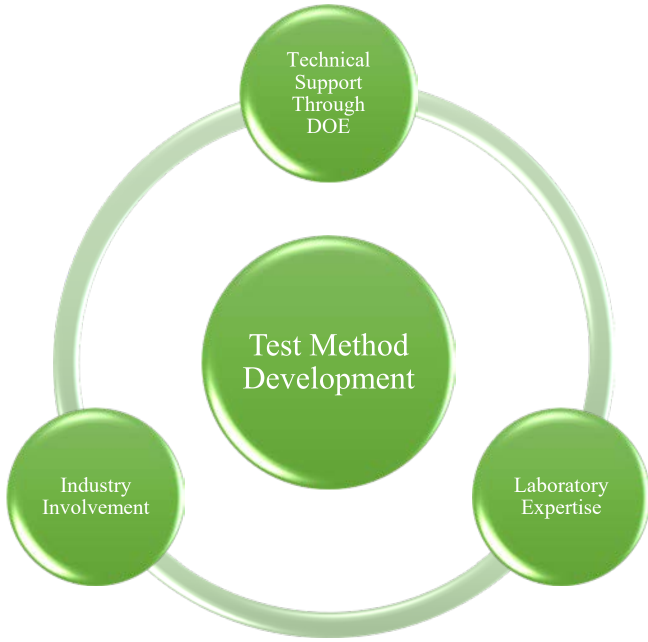

Figure 17. Important support for test method

This project is an example of how technical support provided by the DOE can act as a catalyst for standard development that can provide a needed service for the market. The nature of this test method made development without DOE support impractical. Even with the high cost of the chamber prototype covered by the AQ-SPEC laboratory, the funding to do preliminary testing and to work through the long process of stakeholder engagement and consensus development would have remained a barrier to test method development.

The IAQ sensor test methods developed during this project benefitted from the technical support provided through DOE, as well as from the interest of industry and laboratory partners able to provide technical expertise. Without any of these inputs, the project would likely not have moved forward given the significant technical support and consensus work needed.

4.4 Lessons Learned from the Standards Process

4.4.1 Technical Basis

For the development of any technical standard, it is vital to start with a robust technical basis. This project benefitted from the initial prototype test procedure development by South Coast AQMD's AQ-SPEC laboratory. Having a prototype chamber and procedure in place allowed technical development efforts to focus on adjusting and improving methodologies rather than creating them. For this specific test method, the initial equipment investment is substantial. Having a laboratory already mostly set up to perform validation testing using the draft method made this project possible. In fact, other laboratories that might be interested in conducting IAQ sensor testing, are unlikely to develop a chamber system until a published standard is finalized. AQ-SPEC's taking on the risk of developing a chamber before a published test method, and then adjusting their equipment and procedures to match the final method, will allow other laboratories to participate by following an established path.

4.4.2 Clear, Enforceable, Repeatable Language

A significant undertaking in this project was transitioning descriptions of proprietary test procedures into enforceable standard language that was clear and could be repeated by multiple laboratories. Beyond minor language changes throughout, such as changing flexible language like "may" to enforceable language like "shall," the descriptions of test procedures needed to be more general in some areas and more specific in others.

For example, the prototype test procedure described a system of fans that would produce a well-mixed environment. Well-mixed was not specific enough to be repeatable, so a section was developed to describe a metric for homogeneity in the test chamber so that the test sensors and the probe from the reference monitor would experience the same conditions within the chamber.

An example of a specification that was changed to be more general is the particle filter. To remove particles, a filter is necessary in the chamber system. The original draft included specific filtration specifications, but the test method was changed to reference a filtration standard instead so that multiple equivalent filters could be used.

4.4.3 Consensus Development

Consensus development presented the most challenging aspect of standard development. At any point during the process, any ASTM subcommittee member or committee member could raise an objection or a question that would halt the standard's progress. Any negative ballot or comment either must be resolved, or there must be a formal vote to decide the issue. Because ASTM prefers resolution rather than up or down votes on any issue, this often required in multiple meetings and discussions, and possibly draft language passed back and forth between parties to develop consensus; the result was a robust document with broad support.

Negative ballots often included opposing perspectives on an issue, sometimes introduced over multiple ballots. For example, during the development of the $PM_{2.5}$ test method, several commenters suggested allowing reference monitors to meet a broader variety of standards including international standards. The appeal of this approach is that laboratories around the world might not possess reference monitors that had been through the EPA's FEM or FRM process but could offer equivalent standards. Several other commenters insisted that only FEM monitors be referenced to be sure of the bias in the test method. In this case, consensus discussions with both groups were able to lead to a decision to require FEM or better reference monitors.

4.4.4 Time to Develop

Due to the process issues above, standard test methods take significant time to develop. This project began in late 2017, and *ASTM D8405-21* was not published until September 2021. This standards development process is often driven by volunteers, or by professionals who have full time jobs on top of their standards work. Gaining stakeholder input, development of standard language, laboratory testing, and the official ASTM standard process includes structured timelines and frameworks established for participating and contributing with input, feedback, and comments throughout. This typically cannot be rushed and will likely take several years for any standard approval.

4.5 Future of IAQ Sensor Test Method Efforts

4.5.1 Verification, Research, and Codes/Standards References

Possible Pollutant Sensors Covered by Future Test Methods

- CO
- Formaldehyde
- H_2S
- NO
- NO_2
- NO_x
- O_3
- SO_2
- Ultrafine particles
- VOCs

Figure 18. Possible pollutant sensors covered by future test methods

Published test method standards for IAQ sensors can be used by sensor manufacturers or researchers to understand or even publicize the performance of a sensor. South Coast AQMD's AQ-SPEC laboratory was already performing sensor tests on low-cost IAQ sensors as a way of informing the public about the performance of these sensors. Now that there is a published test method, other laboratories could perform the same service using standardized methodologies. Likewise, manufacturers could perform the same test during development of their products.

Codes and other standards can even reference the test method. There are currently many ASTM references in the building code. For example, the *International Residential Code* (International Code Council 2021) references multiple ASTM test methods related to the fire resistance of materials and assemblies that are required in a home.

If the building code wanted to ensure that any sensor-controlled ventilation system only used reliable sensors, that code could reference the ASTM test method. Likewise, if the building code required IAQ sensors for offices or dwelling units, an ASTM test method could be referenced to require that IAQ sensors that have been tested to that method be installed.

4.5.2 Test Methods for Sensors of Other Pollutants

The goal of this project was always to develop test methods that would be applicable for more than one pollutant. In fact, many sensor systems include sensors for many different pollutants. Some examples measure $PM_{2.5}$, VOCs, CO_2, and NO_2 using multiple sensors in a single package. While the published test method is restricted to sensors for one specific pollutant, this project has established the ability to model future test methods on these early models. The test method models are written so that the same structure could be used for other pollutants, using the same basic phases, with possible additions. For each new substance, different interferents, reference monitors, scrubbers, and other specifications would be needed, but the basic approach would be the same. With consensus developed on many issues for $PM_{2.5}$ sensor testing and next for CO_2 sensor testing, it is likely that future test methods will be easier to develop than these first two models. Future test methods for sensors of other pollutants could include sensors for pollutants listed in Figure 18.

With the groundwork laid for $PM_{2.5}$ sensors and CO_2 sensors, other gases and particles may be as simple as changing some of the specifications. VOCs may be more complicated, especially when it comes to defining exactly which VOCs to use for the test. In the case of ultrafine particles, a market for low-cost ultrafine particle sensors may need to develop before a test method would be worthwhile.

4.5.3 Industry Certification Program

HVI and HARCA participated in the development of the test methods throughout the project, partnering with Newport to recruit interested ventilation industry members for the TAG, promoting the project to their members, and co-presenting with Newport at industry meetings. HVI, an industry association historically representing ventilation manufacturers, describes themselves as, "champions of healthy indoor air working together to advance and promote dependable ventilation practices through product certification, stakeholder education, and codes and standards participation" (HVI 2022b).

HARCA, an HVI affiliate, conducts research and public outreach related to IAQ. Both organizations see IAQ sensors as an important tool for improving IAQ in partnership with their existing ventilation manufacturer stakeholders. HVI operates an esteemed and accredited Certified Ratings Program for fan performance metrics, such as airflow, sound (loudness), and input power. *HVI Publication 916 Air Flow Test Procedure* specifies procedures for testing and rating airflow (HVI 2015), while *HVI publication 915 Procedure for Loudness Rating of Residential Fan Products* specifies procedures for sound testing and loudness rating for residential ventilation equipment (HVI 2016).

Though the HVI Certified Ratings Program's primary purpose is to certify product performance without setting minimum performance requirements, HVI publications are referenced in EPA's *ENERGY STAR® Program Requirements for Residential Ventilating Fans and Canadian Natural Resources Heat/Energy Recovery Ventilators – ENERGY STAR Technical Specifications*, where HVI serves as an approved certification body.

The HVI Certified Products Directory presents certified rating information for more than 3,600 residential ventilation products to the public (HVI 2022a). Existing HVI publications reference consensus-based test method standards for their procedures and add supplementary process requirements, such as annual performance verification and labeling.

HVI and HARCA have begun work on a certification program for IAQ sensors based on ASTM test methods. The program plans to reference *ASTM D8405-21* to start and will add additional test methods for other sensor types as they are completed. This certification represents a new product category for the HVI Certified Ratings Program and will involve outreach beyond ventilation manufacturers to the sensor manufacturer industry. It is likely that HVI will develop minimum performance tolerances for product certification and verification based on input from sensor experts and industry.

As reliable low-cost sensors are tested to *ASTM D8405-21* and achieve HVI certification, these sensors have the potential to provide IAQ tools to a variety of end users, summarized in Figure 19.

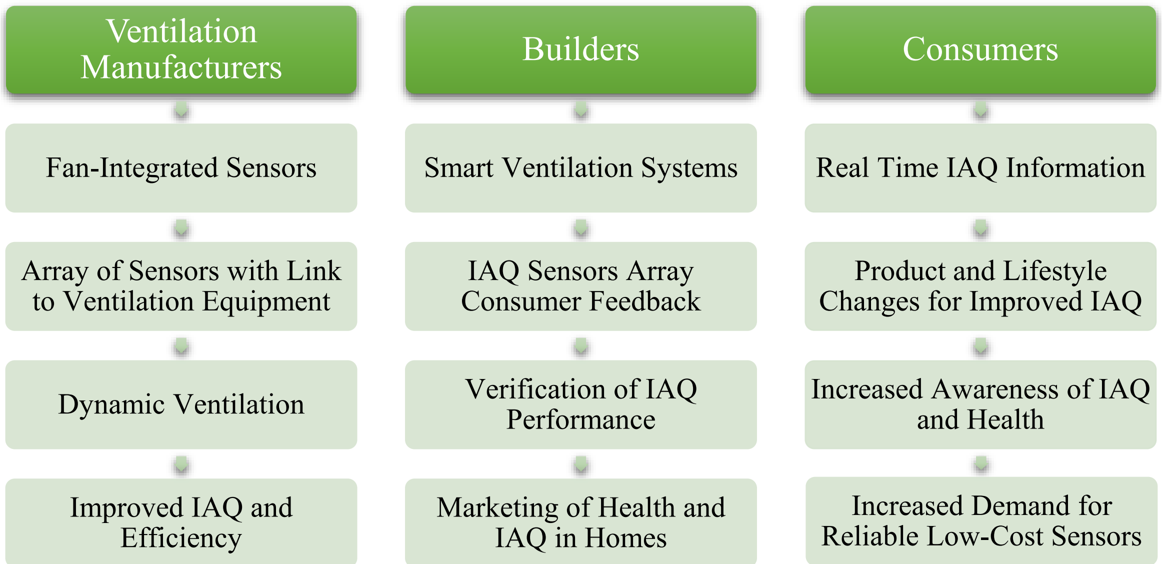

Figure 19. Market deployment of low-cost indoor air quality sensors

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