भारतीय मानक मसौदा

इनडोर और आउटडोर वातावरण में पार्टिकुलेट मैटर के मापन के लिए सेंसर आधारित उपकरणों की प्रदर्शन आवश्यकता

Draft Indian Standard

Performance Requirement of Sensor Based Instruments for Measurement of Particulate Matter in Indoor and Outdoor Environment

(ICS 13.040.20)

Air Quality Sectional Committee, CHD 35	Last Date for Comments: 4th December 2025

FOREWORD

(*Formal clause will be added later*)

The market for sensor-based instruments for monitoring air pollution is growing tremendously due to the affordability and portability of such instruments. The low cost of these instruments makes it possible to use these in dense networks, which in turn give better spatial and temporal data. The fact that people from non-scientific community can use these instruments in their daily lives to monitor the air quality in their surroundings and indoor increase the attraction and demand of these instruments.

However, these instruments are not comparable to regulatory grade instruments in terms of accuracy and precision as they are prone to several interferences caused by atmospheric conditions. Researchers are working towards enhancing the performance of sensors and this technology has the potential to become a vital complementary technology to the regulatory monitoring. Some important facts about sensor technology:

a) Sensor technology is very effective for capturing more detailed temporal and spatial variations
b) With proper calibration methodology and protocol, and quality assurance and quality control processes in place, performance of such instruments can be enhanced.
c) Performance enhancement can also be achieved by improving sensor design and ensuring other elements like the algorithm, corrections (for temperature and relative humidity), instrument design, etc. complement the sensor.
d) It is an evolving field where continued research in the area of sensor application for environmental quality monitoring is taking place.

Draft Indian Standard

PERFORMANCE REQUIREMENT OF SENSOR BASED INSTRUMENTS FOR MEASUREMENT OF PARTICULATE MATTER IN OUTDOOR AND INDOOR ENVIRONMENT

1 SCOPE

This standard prescribes performance requirements, and methods of test for sensor-based instruments used for indicative measurement of particulate matter (PM_{10} and $PM_{2.5}$) in outdoor and indoor environment.

2 REFERENCE

The standards given below contain provisions which through reference in this text, constitute provisions of this standard. At the time of publication, the editions indicated were valid. All standards are subject to revision and parties to agreement based on this Indian Standard are encouraged to investigate the possibility of applying the most recent editions of the standard given below.

IS No.	*Title*
IS 4167 : 2020	Glossary of terms relating to air pollution (*second revision*)

3 TERMINOLOGY

For this standard, the definitions given in IS 4167 shall apply.

3.1 Selectivity

It is the ability of a sensor to identify the particulate matter (PM_{10} and $PM_{2.5}$) of interest from within a complex mixture of pollutants.

3.2 Limit of Detection

The limit of detection (LOD) is the lowest quantity (mass concentration) of PM that a sensor can distinguish from the absence of that PM concentration within a stated confidence limit.

$$\text{LOD} = \frac{3.3\sigma}{S}$$

where,

σ = standard deviation of the linear regression line between the sensor measurements and the corresponding FRM/FEM/reference instrument data; and

S = slope of the linear regression line.

3.3 Response Time

Time taken by sensor to measure and reflect the change in concentration of the pollutant (s) being measured.

3.4 Precision

The degree of repeatability of measurement by a sensor/a group of identical sensors under identical set of conditions. This is often represented using standard deviation.

3.5 Accuracy

It is the maximum difference between the actual value (measured using reference grade instruments) and sensor reading, and can be expressed either as percentage of full scale or in absolute terms. It is a combination of systematic error and random error.

3.6 Uncertainty

Bias from actual value estimated at 95 percent confidence limit.

3.7 Completeness

The number of valid measurement data obtained in actuality from the sensor system compared to the number of measurements that were expected to be obtained under ideal conditions.

3.8 Detection Limit

The minimum target pollutant concentration that can be measured by the instrument with a certain degree of confidence.

3.9 Duration of Measurement

The time interval over which the instrument is programmed to measure and collect data of concentration of target pollutants.

3.10 Measurement Frequency

The time interval between successive measurements. The number of measurements made in a given duration of measurement (**3.9**) can be calculated from this.

3.11 Range of Measurement

The difference between the maximum concentration of target pollutant that an instrument can measure with acceptable degree of confidence and its detection limit.

3.12 Calibration

Testing linearity of operation of sensor-based instruments at minimum 3 points (with respect to particle mass concentration).

3.13 PM_{10}

Inhalable particles, with diameters that are 10 micrometres and smaller.

3.14 $PM_{2.5}$

Fine inhalable particles, with diameters that are 2.5 micrometres and smaller.

4 OPERATION VARIABILITY

4.1 Particulate matter air sensor operation can exhibit variability due to several factors, including sensor drift, changes in aerosol composition and density, size distribution and shape, and environmental conditions including meteorological conditions. These factors can affect the accuracy of PM measurements, and understanding them is crucial for interpreting sensor data.

4.2 The location of a sensor can significantly impact the PM readings due to variations in local sources and atmospheric conditions. Also, different types of PM sensors (e.g., nephelometric, optical particle counters) have varying sensitivities to particle size and composition. Therefore, choosing appropriate sensor types for the specific application and environmental conditions can improve data quality.

5 APPLICATION

Sensor-based instruments are not currently at par with regulatory grade instruments; thus, it is important that the measurement objective of the instruments be identified. The sensor-based instruments characterized in this standard shall not be used for regulatory reasons, policy making, AQI calculation etc; they can be used for the following applications:

   a) Indicative Personal Exposure Monitoring: monitoring the air quality that a single individual is exposed to while doing daily activities;
   b) Indicating Monitoring Data: placing sensors within an existing state/local regulatory monitoring area to fill in coverage Identification of hot spots;
   c) Education: using sensors in educational settings for science, technology, engineering, and math lessons; and
   d) Information/Awareness: using sensors for informal air quality and trend analysis.

While using sensor-based instruments for above applications, it should be kept in mind that values given by sensor based instruments are indicative. The performance of these instruments is subject to periodic calibration and

people from non-scientific communities may not be aware or inclined to do the periodic calibration. In such cases, the performance of these instruments may deteriorate, causing false alarm and panic.

6 INTERFERENCES

6.1 Humidity

Humidity affects the sensor in many ways. The size of hygroscopic particles is dependent on RH, as the particle refractive index and size both are functions of RH. Therefore, it is necessary to determine the threshold RH above which sensor overestimates the concentration. Few sensors based devices also consist of internal heaters that control the threshold RH to prevent overestimation of concentration. Overall, all sensors require the calibration both in laboratory and field condition and correction factor to correct the generated data.

6.2 Temperature

The individual effect of temperature is negligible on the sensor data accuracy, however, the combined effect of ambient temperature and humidity affect the particle morphology. Under low ambient temperature and high RH conditions, the air flow path inside the sensor may form water droplets because of condensation of water vapours, which may deteriorate the data quality and also sensor life. The effects can be observed where temperature diurnal variation is large.

6.3 Air Flow

The sensor data quality is dependent on constant air flow supply inside the detection system. Variation in air flow can affect the aerosol path exposed at a light beam, hence its scattering and consequently output data. Therefore, air flow variation should be controlled within $\pm$ 10 % of defined flow rate in the monitor. Monitor must have proper inlet/outlet to crosscheck air flow rate in the detector module of the unit. The flow rate and its variation needs to be checked with sensitive flow meters for a period of at least 60 min.

6.4 Dust Loading

The maximum exposure limit of particle concentration should be known for the sensor. Deposition of particles on the optics of the photodetector of the sensor may decrease detector measurement efficiency. This information should be mentioned in the product information sheet.

6.5 Other interferences

Wind direction and speed can cause variability in data accuracy, if sensor inlet is exposed to the environment in a different direction. This cause poor sampling of bigger fraction of particles (>2.5 μm). Particle chemical composition, density and shape can influence the sensor results.

7 OPERATION REQUIREMENTS

7.1 Method of Measurement

The instrument shall be including laser scattering or any equivalent aerosol measurement techniques as the technology for measurement of particulate matter concentration. The concentration of particulate matter is reported in μg/m^3.

7.2 Monitoring

Air is sucked in detector module through a defined inlet at constant flow rates of 0.1 lpm or more in continuous mode. Monitor should have a defined suction flow rate for detector in the unit. Flow variation in defined flow rate should not be more than $\pm$ 10% of the reading.

7.3 Power supply

The system shall have 24 h backup (with no grid or solar power). System shall be able to run in 230V $\pm$ 10V, 50 Hz power supply or DC power supply or solar power system for charging the battery of monitor.

7.4 Instrument Housing

The instrument shall be placed in a weather-proof, dust-proof and water-proof enclosure. Dust-proof capability shall be as per IP65.

7.5 Data Storage and Communication

The instrument shall be able to store data for 24 hours in case of power failure or connectivity loss. It shall have in-built data logger with USB port or ethernet/GPRS/Wi-Fi /any relevant new technology for online data downloading through servers/computers/ terminals.

7.6 Environmental Operating Conditions

The instrument can be operated at temperatures ranging from 0 °C – 50 °C and relative humidity range 0 percent – 95 percent.

7.7 Instrument Cleaning and Storage

The instruments shall be cleaned and stored as per manufacturer's instructions.

7.8 RH Temperature and BP Monitoring

Simultaneous Monitoring of RH Temperature and BP by the system is mandatory.

7.9 Reporting Interval

Minimum reporting interval of 1 min or configurable for maximum averaging period of 60 min user selectable

8 CALIBRATION AND PERFORMANCE EVALUATION PROCEDURE

Minimum calibration and performance check on sensor based particulate monitor need to be done at different level as described below:

8.1 At Manufacturer Level

8.1.1 Assembled monitor fitted with sensor and microprocessor and inlet where air flow can be checked must be operated with reference instrument/monitor at least for 3 days (24 hours each day) to record PM_{10}, $PM_{2.5}$, Temp, RH and BP at 15 min recording interval. Units need to be operated in outdoor (open) and indoors (confined) areas by collocating it with reference calibrated instrument/monitor with valid calibration certificate from an accredited lab with valid traceability. The variation in reference and unit under test should not be more than ± 10 percent of the reading.

8.1.2 Recommendation for calibration and testing frequency should also be clearly defined in the manual

8.1.3 Calibration traceability of reference unit used in evaluation need to be provided with supply.

8.2 At Accredited Laboratory Level

Testing and calibration laboratory undertaking testing & calibration performance evaluation of Sensor based unit must have Accreditation for documented scope and at least comply with requirements of ISO/IEC 17025:2017. Lab must have a reference unit duly certified/calibrated by National Metrology Institute (NMI) a body notified by Government of India for such calibration and performance testing work or certification/calibration through an accredited lab with known deviation and uncertainties of the measurements with valid traceability.

8.3 PERFORMANCE EVALUATION PROCEDURE

Different aspects of PM sensor must be checked to determine overall quality of PM sensor. The testing method of sensor shall be performed in laboratory or in field condition. Performance Evaluation Procedure followed at certification body for mentioned parameters for sensor based particulate monitor is out lined in Annex- A for ready reference and clarity. To undertake performance evaluation of defined parameters in Annex-A, the testing approach and outline of method is given below:

8.3.1 Field Comparison

Statistical calculations to be done on collected performance evaluation results follow procedure given in Annex-B.

8.3.1.1 *Materials and Equipment*

a) Reference $PM_{2.5}$ and PM_{10} sampler (gravimetric method);
b) PTFE filters (47 mm diameter, 2 μm pore size);
c) Three (3) or more complete unit fitted with air sensors having the same make, model, and firmware version;
d) Calibrated $PM_{2.5}$ and PM_{10} monitor/sampler;

    e) Calibrated RH monitor;

    f) Calibrated Temperature monitor;

    g) Calibrated BP monitor; and

    h) Calibrated Gravimetric measurement weighing facility.

8.3.1.2 *Method*

    a) Co-locate the reference $PM_{2.5}$ and PM_{10} sampler and three sensors of the same model at ambient location; Co-location guidelines

        i) Mount sensors within 2 meter to 3 metre horizontal of the reference monitor;

        ii) Mount sensors in a location where they are exposed to unrestricted air flow;

        iii) Ensure the air sampling inlet for the sensors are within a height of ± 1 meter vertically of the air sampling inlet of the reference monitor;

        iv) Mount identical sensors ~1 meter apart from each other;

        v) If necessary, install sensors within a weather-protective shelter/enclosure that maintains ample air flow around the sensor;

    b) Monitor temperature, humidity and pressure of ambient environment;

    c) Start the sampling simultaneously (at the same time) and note down the start time and make sure the time shown by reference instrument and PM sensor is common otherwise calibrate the timing with common standard clock;

    d) Stop the sampling at 24 h of reference $PM_{2.5}$ and PM_{10} sampler;

    e) Record the daily start and stop time;

    f) Repeat the step 1 to 4 for a minimum of 10 samples; and

    g) Record the data generated from PM sensor, reference monitors.

8.3.2 Laboratory chamber testing

This test measures the Temperature and humidity effect over the sensor, drift and accuracy of sensor. Statistical calculation can be referred to Annex C.

8.3.2.1 *Materials and Equipment*

    a) Environmental chamber (Temperature 15 °C to 40 °C, RH: 35 percent to 95 percent, PM levels :10 $\mu g/m^3$ to 500 $\mu g/m^3$). Testing should be performed at least three different conditions.

Specification/selection criteria

        i) Ability to control, maintain, and monitor T, RH, and PM concentrations;

        ii) recommended ranges based on testing conditions outlined in this report: Temperature 15 °C to 40 °C; RH: 35 percent to 95 percent; PM of desired concentration of 10 $\mu g/m^3$ to 500 $\mu g/m^3$;

        iii) Ability to maintain the particle size distribution, composition, and concentration;

        iv) Ability to maintain atmospheric pressure by balancing the incoming flow with the sampling and vent flow;

        v) Allows for air to be well-mixed;

        vi) Capable of accommodating three (3) or more air sensors;

        vii) Sampling ports should not be obstructed and allow for sufficient sampling flow;

        viii) The particle generation system should be positioned above the exposure chamber and connected with as few bends as possible to prevent particle loss and build-up before particles enter the chamber; and

        ix) The PM FEM monitor should be mounted directly below the sampling chamber to reduce particle loss in the sampling line due to bends.

    b) Calibrated Temperature, humidity and pressure probe and data logger;

    c) Certified reference material: Ambient PM dust;

    d) Reference particle monitor (continuous);

    e) Aerosol generator;

    f) Neutraliser;

    g) Mixing fan; and

    h) Aerosol sampling probes

8.3.2.2 *Method*

a) Place three sensors of the same model inside the environmental chamber;
b) Place the aerosol sampling probes inside the chamber;
c) Connect the outlet of probes to the reference monitor placed outside the environmental chamber for reference sampling;
d) Seal the chamber to prevent particle intrusion from outside;
e) Monitor temperature, humidity and pressure of the chamber;
f) Set the temperature and humidity of the environmental chamber (mentioned in Table A and B) and wait till it gets stabilized. Ensure the pressure inside is equivalent to ambient pressure;
g) Monitor and log the zero-particle concentration with a reference monitor and note the minimum detection limit (zero) of the sensor;
h) Start an aerosol generator coupled with a neutralizer placed outside the chamber and mix the particles in a chamber by mixing fans;
i) Maintain the chamber dust particle concentration as desired test condition mentioned in Table A, B and C;
j) Monitor and log the particle concentration with reference monitor and sensor; and
k) This will give data of linearity between reference monitor and sensor both at different temperature, humidity and PM concentration.

Table A: RH Test Condition

Sl No.	Parameter	Reference Set point
(1)	(2)	(3)
i)	PM concentration (2.5 or 10)	(60 ± 5) percent $\mu g/m^3$
ii)	Temperature	25 °C $\pm$ 1 °C
iii)	Relative Humidity	(85 ± 5) percent

Table B: Temperature test condition

Sl No.	Parameter	Reference set point
(1)	(2)	(3)
i)	PM concentration (2.5 or 10)	(60 ± 5) percent $\mu g/m^3$
ii)	Temperature	40 °C $\pm$ 1 °C
iii)	Relative Humidity	(40 ± 5) percent

Table C: Accuracy and drift test condition

Sl No.	Parameter	Reference set point
(1)	(2)	(3)
i)		Very low (10 ± 10) percent $\mu g/m^3$
		Low (35 ± 10) percent $\mu g/m^3$

	PM concentration (2.5 or 10)	Mid (100 ± 5) µg/m^3
		High (200 ± 2) percent µg/m^3
		Higher 350 µg/m^3 ± 2 µg/m^3
ii)	Temperature	25 °C ± 1 °C
iii)	Relative Humidity	(40 ± 5) percent

9 INTERMEDIATE CHECKS

Intermediate check of instrument shall be done, against reference standard instrument. Maximum acceptable error is ±10 percent.

10 PERFORMANCE REQUIREMENTS

The sensor-based instruments shall satisfy the performance requirements prescribed in Table 1, for definitions check Annex D.

Table 1 Performance Requirements of Sensor Based Instruments

(*Clause* 10)

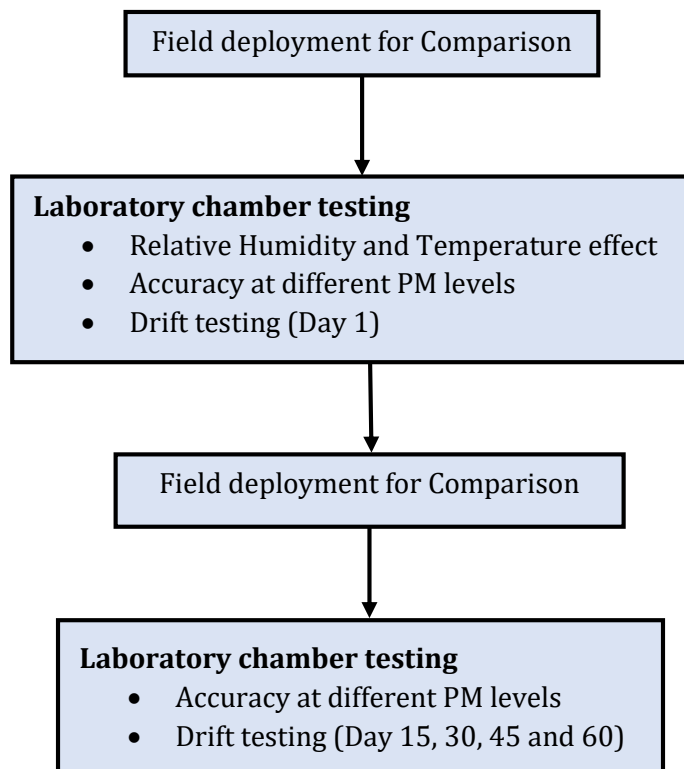| Sl. No.	Performance Characteristics	Laboratory	Field
(1)	(2)	(3)	(4)
i)	Range of measurement , µg/m^3	PM$_{2.5}$: 10 to 500 PM$_{10}$: 10 to 500	PM$_{2.5}$: 10 to 500 PM$_{10}$: 10 to 500
ii)	Minimum Detection Limit, µg/m^3	10	10
iii)	Minimum detectable size, µm	0.3	0.3
iv)	Precision on reported value, percent, *Min*	± 15	± 20
v)	Accuracy, percent	25	25
vi)	Response time, *s*	≤ 30	≤ 30
vii)	Completeness, percent	> 90	> 90
viii)	Measurement Uncertainty, percent	PM$_{2.5}$: 30 percent at 300 µg/m^3 PM$_{10}$: 30 percent at 500 µg/m^3	PM$_{2.5}$: 30 percent at 300 µg/m^3 PM$_{10}$: 30 percent at 500 µg/m^3
ix)	Inter-model variability, percent , *Max*	± 15	± 20

ANNEX-A

(*Clause* 8.3)

PERFORMANCE EVALUATION

A-1 Performance evaluation procedure followed at certification body for mentioned parameters for sensor based particulate monitor is given below:

a) Field Comparison
    Evaluation of sensor at ambient outdoor site provides information on PM sensor performance that is relevant to real world condition and allow user to predict how the sensor might perform in similar condition.

b) Relative Humidity and Temperature effect
    Compare a test PM concentration with elevated RH and temperature to see effect on PM sensor.

c) Accuracy at low, mid and high concentration
    Determine PM sensor performance when exposed to test conditions with low, mid and high concentrations.

d) Drift
    Compare the PM sensor response to test PM concentration before and after the sensors are operated for specified time period of 15, 30, 45 and 60 days in air.

A-2 To test the above parameters, the testing approach and outline of method is given below:

Field deployment for Comparison

↓

Laboratory chamber testing
- Relative Humidity and Temperature effect
- Accuracy at different PM levels
- Drift testing (Day 1)

↓

Field deployment for Comparison

↓

Laboratory chamber testing
- Accuracy at different PM levels
- Drift testing (Day 15, 30, 45 and 60)

ANNEX-B

(*Clause* 8.3.1)

FIELD COMPARISON CALCULATIONS

B-1 DAILY AVERAGES

Performance metrics are calculated from daily (24 h) averaged data. Any FRM/FEM, sensor, RH, and/or T data collected as sub-daily time intervals will first need to be averaged up to daily averages. In calculating these averages, a 75 percent data completeness requirement for each 24 h interval should be imposed. For example, a PM sensor recording concentration measurements every hour would require a minimum of 18 valid measurements in order to calculate a valid 24 h averaged concentration [i.e., (18/24) * 100 percent = 75 percent].

$$x_{kdj} = \frac{1}{n}\sum_{i=1}^{n} c_{ij}$$

where

x_{kdj} = 24 h averaged measurement k for day d and instrument j ($\mu g/m^3$, °C, prenet RH);

n = number of instrument measurements per 24 h period; and

c_{ij} = measurement from instrument j for time i of the 24 − hour period ($\mu g/m^3$, °C, precent RH).

B-2 DEPLOYMENT AVERAGES

The average concentrations and meteorological parameters for the entire 30-day deployment should be reported. Deployment averaged measurements should be calculated from valid 24 h averaged data for each field test.

$$\overline{x_k} = \frac{1}{M}\sum_{j=1}^{M}\left[\frac{1}{N}\sum_{d=1}^{N} x_{dj}\right]$$

where

$\overline{x_k}$ = deployment averaged measurement k for a field test ($\mu g/m^3$, °C, percent RH);

M = number of identical instruments operated simultaneously during a field test;

N = number of 24 h periods during which all identical instruments are operating and returning valid averages over the duration of the field test; and

x_{dj} = valid 24-hour averaged measurement for day d and instrument j ($\mu g/m^3$, °C, percent RH).

B-3 PRECISION

Precision between identical sensors should be characterized by two metrics: standard deviation (SD) between measurements and coefficient of variation (CV). These metrics should be calculated for the base testing field deployments using data during which all identical sensors are operating and returning valid 24 h averaged measurements

$$SD = \sqrt{\frac{1}{(N \times M) - 1}\sum_{j=1}^{M}\left[\sum_{d=1}^{N}\left(x_{dj} - \overline{x}_d\right)^2\right]}$$

where

SD = standard deviation of 24 hour averaged sensor PM concentration measurements ($\mu g/m^3$);

M = number of identical sensors operated simultaneously during a field test;

N = number of 24-hour periods during which all identical instruments are operating and returning valid averages over the duration of the field test;

x_{dj} = 24−hour averaged sensor PM concentration for day d and sensor j ($\mu g/m^3$);and

$\bar{x}_d$ = 24−hour averaged sensor PM concentration for day d ($\mu g/m^3$).

$$CV = \frac{SD}{\bar{x}} \times 100$$

where

CV = coefficient of variation (percent);

SD = standard deviation of 24 h averaged sensor concentration measurements ($\mu g/m^3$); and

$\bar{x}$ = deployment averaged sensor PM2.5 concentrations for a field test ($\mu g/m^3$).

B-4 BIAS AND LINEARITY

A simple linear regression model can demonstrate the relationship between paired 24-hour averaged sensor and FRM/FEM PM measurements. Using a simple linear regression model (y = mx + b) with the sensor PM measurements as the dependent variable (y) and the FRM/FEM PM measurements as the independent variable (x), calculate the slope (m), intercept (b), and the coefficient of determination (R^2). A simple linear regression model for each identical sensor (with corresponding graphical figures) are recommended. Comparison of the figures and these metrics across identical sensors can be helpful in further visualizing sensor precision. Sensors with very similar regression models and higher R^2 values are typically more precise than those with different regression models and lower R^2 values.

B-5 ERROR

The root mean square error (RMSE) is one metric that can be used to help understand the error associated with sensor PM2.5 concentration measurements. The interpretation of this value is slightly more straightforward because it is calculated in concentration units. Using data during which all sensors are reporting valid 24 h averaged measurements, the sensor and FRM/FEM PM measurement calculations are compared. This equation assumes only one FRM/FEM instrument will be running. If multiple FRM/FEM instruments are running, separate testing reports can be generated for each.

$$RMSE = \sqrt{\frac{1}{(N \times M)} \sum_{j=1}^{M} \left[\sum_{d=1}^{N} (x_{dj} - R_d)^2 \right]}$$

where

$RMSE$ = root mean square error ($\mu g/m^3$);

M = number of identical sensors operated simultaneously during a field test;

N = number of 24-hour periods during which all identical instruments are operating and returning valid averages over the duration of the field test;

X_{dj} = valid 24 h averaged sensor PM concentration for day d and instrument j ($\mu g/m^3$); and

R_d = valid 24 h averaged FRM/FEM PM concentration for day d ($\mu g/m^3$).

B-6 EFFECT OF METEOROLOGY

Here are several ways to investigate the potential influence using data from the field tests but, no single plot has proven useful in visualizing these effects for all sensor types. Here, several graphical ways to plot the data are suggested to try to understand the effect of meteorology. Additional ways may exist. Testers are encouraged to illustrate the effects of meteorology using one or more graphs that show the most profound or consistent effects for each field deployment.

B-7 POTENTIAL SCATTER PLOTS

Sensor measurements should be plotted on the y-axis (dependent variable) with the meteorological parameter measurements (as measured by the T and RH monitors, rather than on-board T and RH sensor measurements) on the x-axis (independent variable). Normalized concentration (in other words, the ratio of sensor to FRM/FEM

concentration), concentration difference, absolute concentration difference, and DP calculations are discussed in the list below. It is recommended that testers choose plots from this list.

i)   24 h averaged normalized sensor PM concentration vs. 24 h averaged DP;
    24 h averaged normalized sensor PM concentration vs. 24 h averaged RH;

ii)   24 h averaged normalized sensor PM concentration vs. 24-h averaged T;

iii)   24 h averaged concentration difference between the sensor and FRM/FEM PM concentration vs. 24 h averaged DP;

iv)   24 h averaged concentration difference between the sensor and FRM/FEM PM concentration vs. 24 h averaged RH;

v)   24 h averaged concentration difference between the sensor and FRM/FEM PM concentration vs. 24 averaged T;

vi)   24 h averaged absolute concentration difference between the sensor and FRM/FEM PM concentration vs. 24 h averaged DP;

vii)   24 h averaged absolute concentration difference between the sensor and FRM/FEM PM concentration vs. 24 h averaged RH; and

viii)   24 h averaged absolute concentration difference between the sensor and FRM/FEM PM concentration vs. 24 h averaged T.

ANNEX C

(*Clause* 8.3.2)

LABORATORY CHAMBER TESTING CALCULATIONS

C-1 TEST AVERAGES

Test averaged measurements should be calculated from valid averaged data collected during the steady state period for each test.

$$\overline{x_k} = \frac{1}{M}\sum_{j=1}^{M}\left[\frac{1}{N}\sum_{h=1}^{N}x_{ktj}\right]$$

where

$\overline{x_k}$=deployment averaged measurement k for a field test ($\mu g/m^3$, °C, precent RH);

M =number of identical instruments operated simultaneously during a field test;

N =number of 24 h periods during which all identical instruments are operating and returning valid averages over the duration of the field test; and

x_{ktj} = valid 24 h averaged measurement for day d and instrument j ($\mu g/m^3$, °C, percent RH).

C-2 PRECISION

Precision between identical sensors can be characterized by two metrics: standard deviation (SD) between measurements and coefficient of variation (CV). This metric should be calculated from valid averaged data collected during the mid-concentration test condition during the post-aging (Day 15,45,60) drift test.

$$SD = \sqrt{\frac{1}{(N \times M) - 1}\sum_{j=1}^{M}\left[\sum_{t=1}^{N}(x_{tj} - \overline{x}_t)^2\right]}$$

where

$SD =$ standard deviation of 24 hour averaged sensor PM concentration measurements ($\mu g/m^3$);

$M =$ number of identical sensors operated simultaneously during the chamber test;

$N =$ number of valid time intervals during which all identical instruments are operating and returning valid averages over the duration of the chamber test;

$x_{tj} =$ averaged sensor PM concentration for time interval t and sensor j ($\mu g/m^3$); and

$\overline{x}_t =$ test averaged sensor PM concentration for day t ($\mu g/m^3$).

$$CV = \frac{SD}{\overline{x}} \times 100$$

where

$CV =$ coefficient of variation (Precent);

$SD =$ standard deviation of 24 h averaged sensor PM concentration measurements ($\mu g/m^3$); and

$\overline{x} =$ deployment averaged sensor PM2.5 concentration for a field test ($\mu g/m^3$).

C-3 BIAS AND LINEARITY

A simple linear regression model can demonstrate the relationship between paired averaged sensor and FEM PM measurements. During enhanced testing, pooling the data collected during the steady state period of the low and mid concentration test conditions during the post-aging (Day 60) drift test and the high and higher concentration tests will reflect data collected under similar T and RH conditions. Using a simple linear regression model (y = mx + b) with the sensor PM2.5 measurements as the dependent variable (y) and the FEM PM2.5 measurements

as the independent variable (x), calculate the slope (m), intercept (b), and the coefficient of determination (R2) for each test.

C-4 ERROR

The root mean square error (RMSE) is one metric that can be used to help understand the error associated with sensor PM concentration measurements. The interpretation of this value is slightly more straightforward because it is calculated in concentration units. This metric should be calculated from valid averaged data collected during the mid-concentration test condition during the post-aging (Day 60) drift test. Using data during which all sensors are reporting valid time averaged measurements, the sensor and FEM PM measurement calculations are compared. This equation assumes only one FEM instrument will be running. If multiple FEM instruments are running, separate testing reports can be generated for each.

$$RMSE = \sqrt{\frac{1}{(N \times M)} \sum_{j=1}^{M} \left[\sum_{t=1}^{N} (x_{tj} - R_t)^2 \right]}$$

where,

$RMSE =$ root mean square error ($\mu g/m^3$);

$M =$ number of identical sensors operated simultaneously during a field test;

$N =$ number of 24-hour periods during which all identical instruments are operating and returning valid averages over the duration of the field test;

$x_{tj} =$ averaged sensor PM concentration for time interval t and instrument j ($\mu g/m^3$); and

$R_t =$ averaged FRM/FEM PM concentration for time t ($\mu g/m^3$).

C-5 EFFECT OF RELATIVE HUMIDITY (RH)

The RH tests on sensor measurements involve two steps: 1) collecting data during steady state at a prescribed PM concentration at 40 percent RH, and 2) collecting data during steady state at the same prescribed PM concentration at 85 percent RH. The effect of RH is the difference between these two measurements.

$$\overline{x_{RH}} = \overline{x_{(RH=85\%)}} - \overline{x_{(RH=40\%)}}$$

where:

$\overline{x_{RH}} =$ test averaged influence of RH on sensor measurements ($\mu g/m^3$);

$\overline{x_{(RH=85\ percent)}} =$ test averaged sensor PM concentration for the portion of the chamber test when the RH is 85% ($\mu g/m^3$); and

$\overline{x_{(RH=40\ percent)}} =$ test averaged sensor PM concentration for the portion of the chamber test when the RH is 40 percent ($\mu g/m^3$).

C-6 EFFECT OF TEMPERATURE (T)

The T tests on sensor measurements involve two steps: 1) collecting data during steady state at a prescribed PM concentration at 25 °C, and 2) collecting data during steady state at the same prescribed PM concentration at 40 °C. The effect of T is the difference between these two measurements.

$$\overline{x_T} = \overline{x_{(T=40)}} - \overline{x_{(T=20)}}$$

where

$\overline{x_T} =$ test averaged influence of T on sensor measurements ($\mu g/m^3$);

$\overline{x_{(T=40)}} =$ test averaged sensor PM concentration for the portion of the chamber test when the RH is 40 °C ($\mu g/m^3$); and

$\overline{x_{(T=20)}}$ =test averaged sensor PM concentration for the portion of the chamber test when the T is 20 °C ($\mu g/m^3$).

C-7 DRIFT

The drift tests involve measuring the drift at two PM concentrations: 1) at a low concentration of 10 µg/m^3, and 2) at a mid-concentration of 100 µg/m3 which is relevant for health messaging. For each PM concentration, the drift measurement includes two separate chamber tests. The first will be conducted to determine the steady state concentration for the prescribed PM concentration. The sensors will then be operated continuously and tested again at least 60 days later to see if the measurement has drifted. The amount of drift will be quantified for both PM concentrations by the difference in the measurement over the 60-day period.

$$\overline{x_{C_{drift}}} = \overline{x_{C_{(day=60)}}} - \overline{x_{C_{(day=1)}}}$$

where

$\overline{x_{C_{drift}}}$ = test averaged sensor drift at PM concentration C over the course of 60 days ($\mu g/m^3$);

$\overline{x_{C_{(day=60)}}}$ = test averaged sensor PM concentration at PM concentration C after 60 days of operation following the start of the drift test ($\mu g/m^3$); and

$\overline{x_{C_{(day=1)}}}$ = test averaged sensor PM concentration at PM concentration C at the beginning of the drift test ($\mu g/m^3$).

C-8 ACCURACY AT HIGH CONCENTRATIONS

The accuracy at high concentrations test involves testing the sensor response at a high PM concentration which is relevant for health messaging and a higher PM concentration which is relevant for PM events such as wildfires. The accuracy of the sensor measurement will be determined by the difference between the sensor and FEM measurements.

$$\overline{x_\Delta} = \overline{x_{sensor}} - \overline{x_{ref}}$$

where

$\overline{x_\Delta}$ = test averaged difference between the sensor and FEM PM concentrations ($\mu g/m^3$);

$\overline{x_{sensor}}$= test averaged sensor PM concentration ($\mu g/m^3$); and

$\overline{x_{ref}}$ = test averaged FEM PM concentration ($\mu g/m^3$).

ANNEX D

(*Clause* 10)

SENSOR PERFORMANCE EVALUATION AND METRICS

The performance metrics based on testing of the parameters given in table 1 are summarised in the table below:

Sl No.	Test type	Metric	Description
(1)	(2)	(3)	(4)
i)	Field comparison		
		Precision	Variation around the mean of a set of measurements reported concurrently by three or more sensors of the same type collocated under the same sampling conditions. Precision is measured here using the standard deviation (SD) and coefficient of variation (CV).
		Bias	The systematic (non-random) or persistent disagreement between the concentrations reported by the sensor and reference instruments. Bias is determined here using the linear regression slope and intercept.
		Linearity	A measure of the extent to which the measurements reported by a sensor are able to explain the concentrations reported by the reference instrument. Linearity is determined here using the coefficient of determination (R^2).
		Error	A measure of the disagreement between the pollutant concentrations reported by the sensor and the reference instrument. Error is measured here using the root mean square error (RMSE) and normalized root mean square error (NRMSE).
ii)	Laboratory Chamber testing		
		Precision	Variation around the mean of a set of measurements reported concurrently by three or more sensors of the same type collocated under the same sampling conditions. Precision is measured here using the standard deviation (SD) and coefficient of variation (CV).
		Bias	The systematic (non-random) or persistent disagreement between the concentrations reported by the sensor and reference instruments. Bias is determined here using the linear regression slope and intercept.
		Linearity	A measure of the extent to which the measurements reported by a sensor are able to explain the concentrations reported by the reference instrument. Linearity is determined here using the coefficient of determination (R^2).

		Error	A measure of the disagreement between the pollutant concentrations reported by the sensor and the reference instrument. Error is measured here using the root mean square error (RMSE) and normalized root mean square error (NRMSE).
		Effect of Relative Humidity (RH)	A positive or negative measurement response caused by variations in RH and not by changes in the concentration of the target pollutant.
		Effect of Temperature (T)	A positive or negative measurement response caused by variations in ambient T and not by changes in the concentration of the target pollutant
		Drift	A change in the response or concentration reported by a sensor when challenged by the same pollutant concentration over a period of time during which the sensor is operated continuously
		Accuracy at High Concentrations	A measure of the agreement between the pollutant concentrations reported by the sensor and the reference instrument during high concentration levels