“Integrating Sensor Monitoring Technology into the Current Air Pollution Regulatory Support Paradigm: Practical Considerations”

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Abstract

It is well-known that air pollution has adverse impacts on human health[1]. In the US, criteria air pollutants are monitored using Federal Reference Method (FRM) and Federal Equivalent Method (FEM) monitors/analyzers/samplers[2] which determine if measured levels exceed the National Ambient Air Quality Standards (NAAQS). The US Environmental Protection Agency (EPA) along with state, local, and tribal governments operate FRM and FEM instruments to assess compliance with US air pollution standards which are designed to protect human and ecosystem health. A new category of air pollution monitoring instruments called 'sensors' have emerged and have implications for the current US air monitoring strategy. Sensors have the potential to be used in compliance monitoring, however a number of considerations need to be made. The paper will discuss those considerations and potential approaches for incorporating sensors into the US air monitoring network.

Current Air Pollution Monitoring Approach

Nationwide air pollution monitoring in the US can be traced to the Clean Air Act (CAA) of 1970. Air pollution monitoring occurred before the 1970 CAA, but did not cover the entire nation and was not managed through a systematic program of standard methods, analyses, testing protocols, and monitor designations for different pollutants. As monitoring technology progressed, EPA's review process evolved to incorporate new methodological approaches to air pollution monitoring. Deciding how to include new technologies into EPA's monitoring strategy is an ongoing process.

Clean Air Act

Section 103 of the CAA (1970) gave EPA authority to develop methods for measuring air pollutants[3]. Under this authority, EPA created a network of air pollution monitors in conjunction with states, tribes, and US territories to measure concentrations of the six criteria air pollutants subject to the National Ambient Air Quality Standards (NAAQS) requirements (40 Code of Federal Regulations [CFR] Parts 50-59)[4]. The two sets of NAAQS requirements are primary NAAQS, focused on protection of human health and secondary NAAQS, focused on protecting ecosystems and property/built environment. 'Criteria pollutants' are designated by the EPA Administrator as having negative impact on health and welfare in the US. Criteria pollutants include: sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), particulate matter (PM_{10} and $PM_{2.5}$), ozone (O_3), and lead (Pb).

Federal Reference Method (FRM)

When an air pollution measurement device is designated as an FRM, this indicates it has been developed to a clearly defined standard for a specific criteria pollutant[s] and has completed a rigorous testing and analysis protocol. Successful completion of this process and designation as a 'reference method' means that the instrument can be used to monitor compliance for the appropriate primary and/or secondary NAAQS standard for a particular criteria pollutant[s]. FRMs incorporate established technologies defined in 40 CFR Part 50 for each criteria pollutant as follows: **i)** SO_2 – Appendix A and A-1; **ii)** CO – Appendix C; **iii)** O_3 – Appendix D; **iv)** NO_2 – Appendix F; **v)** Pb – Appendix G; **vi)** PM_{10} and $PM_{2.5}$ – Appendices J and N respectively.

Federal Equivalent Method (FEM)

Air pollution measurement devices incorporating new technologies are tested and evaluated through the equivalent method process before use in the US air monitoring network. New instruments are designated as FEMs for compliance monitoring of NAAQS. Equivalent methods for criteria pollutants are defined in 40 CFR Part 53 in Subparts B, D, and E with the exception of lead (Pb) which does not have an FEM. Subpart C contains test and measurement requirements for the FEMs. Designation of FRMs and FEMs is the stated responsibility of EPA's National Exposure Research Laboratory (NERL) 40 CFR 53.4**.**

Air Pollution Monitoring

Air pollution monitoring is an important component in EPA's risk mitigation strategy[5]. Knowledge of air pollutant concentrations through a focused monitoring program provides scientists with the ability to assess population exposure levels, provide information on health impacts, and inform decision makers on risk mitigation strategies for reducing air pollution at its various sources. EPA's compliance monitoring is supported by a research effort to ensure that monitors maintain a high level of precision, accuracy, sensitivity and operational capability when measuring air pollutants. The role of air pollution compliance monitoring in EPA's risk mitigation strategy is illustrated in Figure 1.

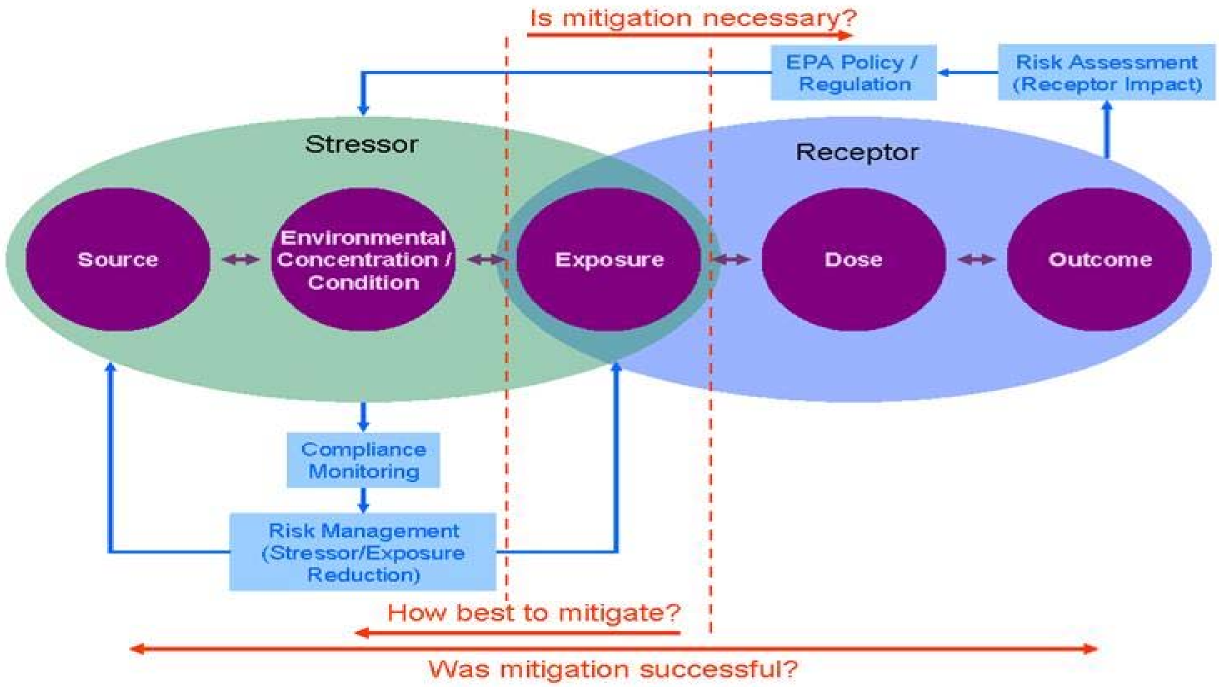

Figure 1. Role of Air Pollution Compliance Monitoring in EPA's Risk Mitigation Strategy (adapted from[5])

Monitoring ambient air quality for NAAQS compliance requires use of either FRMs or FEMs as specified in Section 2.1 of Appendix C to 40 CFR Part 58. Other approaches are used to measure air pollutants outside the compliance monitoring context and they provide information to supplement compliance monitoring. Application of FRMs/FEMs and non-compliance methods of monitoring in an integrated fashion can improve our understanding of how pollutant concentrations vary in space and time.

Regulatory Ambient Air Monitoring

Since 1970, EPA has evolved its approach in monitoring ambient air pollution. Initially, the philosophy transitioned from defining 'methods' to defining 'reference methods' (FRMs). With FRMs, EPA clearly defined and standardized how to implement compliance monitoring. Then equivalent methods were included with reference methods to provide a protocol for inserting new technology into the compliance network, and for upgrading reference methods.

Non-Regulatory Ambient Air Monitoring

Sensors are currently used in non-regulatory monitoring along with other air pollution measurement techniques. A brief discussion of the other techniques provides insight into where sensors are positioned in this context. Mobile monitoring with instrumented vehicles (e.g., automobile, truck, etc.) has been used to measure near-road emissions of non-regulated air pollutants such as ultrafine particles[6]. These measurements used in concert with compliance monitors can infer concentration gradients for small regions. Remote Sensing and "passive" fence-line monitoring measures area source fugitive emissions, providing information on non-criteria hazardous air pollutants such as benzene[7]. Satellite-based instruments like the MODIS (Moderate Resolution Imaging Spectroradiometer) package carried onboard NASA's Aqua and Terra satellites provides a column-integrated measure of $PM_{2.5}$ estimated from Aerosol Optical Depth (AOD)[8]. Other satellites such as OMI (Ozone Monitoring Instrument) and TOMS (Total Ozone Mapping Spectroscopy) provide column-integrated estimates of ozone and other atmospheric gases[9]. Satellites are particularly useful in areas without monitors.

Instrumented aircraft like those in the joint NASA/EPA DISCOVER-AQ (**D**eriving **I**nformation on **S**urface Conditions from **CO**lumn and **VER**tically Resolved Observations Relevant to **A**ir **Q**uality) Project measure ambient concentrations at altitude and correlate them with ground-based monitors. Balloons measure above-ground concentrations and can be used to track regional pollutant movement[10]. In areas without pollution monitors, grid-based, Eulerian, photochemical dispersion air quality models such as CMAQ and CAMx are applied to 'fill-in' gaps in monitor coverage area to facilitate health studies[11]. Model estimates of air pollutant concentrations are used for areas without FRM or FEM monitors.

Data Fusion combines monitor measurements with model estimates. First-generation Hierarchical Bayesian Models (HBM) statistically 'weigh' monitor (a point measurement) and model output (grid cell: 12 km or 36 km square), using monitor values near monitors, while using model values in areas without monitors. The detail of the statistical approach used in HBM is cited in the literature[12]. A single average concentration is provided for each model grid cell and a concentration surface is generated containing 'fused' monitor and model data. Second-generation Downscaler Models (DS) contain enhanced HBM algorithms and provide concentration estimates for specific locations[13]. The data fusion approach has been used successfully with model, monitor, and satellite data inputs[8].

Sensors in Regulatory Ambient Air Monitoring

Sensors are a new technology that is well-described in the literature[14]. Sensors are small, inexpensive monitoring devices representing a 'new-style' of air pollution measurement devices[15]. Like other methods, they provide information which augments compliance monitors. Sensors have already been applied in different environments, but have not been formally used in a compliance monitoring context. Some sensors have undergone preliminary testing at EPA's NERL (Research Triangle Park, NC) and will be evaluated in the field in Houston TX in September 2013 during the DISCOVER-AQ Study.

EPA developed a draft roadmap to guide its approach in use and application of sensors[16]. A summary of sensor characteristics are presented in Table 3-3. There are two general sensor measurement types/categories, gas and particle[17]. Current gas sensors operate using either electrochemical, metal oxide, or spectroscopic technologies. Particle sensors measure particulate matter (PM) by measuring particle mass directly or indirectly by light scattering. Some sensors also measure light absorption, which can be a surrogate for black carbon and ‘brown’ carbon[18]. The application of sensors in a regulatory air monitoring context requires prior analysis, characterization, evaluation, and approval as implemented through the 40 CFR Part 53 evaluation protocols which are described throughout the remainder of this paper.

Table 1. Summary: Sensor Types and Characteristics (adapted from[19])

Sensor Type	**Pollutants Measured (criteria)**	**Range/ Resolution**	**Interferences [IF]**	**Response (seconds)**	**Operating Conditions**	**Setup**	**Other**
Electro-chemical	**CO**, **SO_2**, NH_3, H_2S	**1** ppb to **10-1200** ppm	**SO_2** [**IF**]: Cl, CO, $H_2O_{(g)}$, C_3H_8, C_4H_8, C_7H_8	1-70	15-90% RH 0-40° C	fixed/ hand-held/ portable	**Short life** (1-2 years)
Metal oxide	Non-CH_4 hydrocarbons (NHMC), C_6H_6, CH_4, total VOCs, NH_3, **CO**, **NO_2**, **SO_2**, NO_x	**0.1** to **25-100** ppm (**1 ppb?**: NO_2, CH_4, C_6H_6)	**CO** [**IF**]: $H_2O_{(g)}$, CO_2, H_2	60-180	10-90% RH -10-50° C	fixed/ hand-held/ portable	Sensitive to RH, T, P: requires recalibration (**sensor drift**)
Spectroscopic	NO (chemiluminescence [CL]), CH4, VOCs (non-dispersive infrared: NDIR)	**9 ppb** (CL) or **1-100%** (NDIR)	NO [**IF**]: H_2S, CO_2, **O_3**, H_2O, **NO_2**, **SO_2**, NH_3	20-60	0-95% RH -40-55° C	fixed/ hand-held	More selective sensors are more expensive
Particle	**PM** (**0.1** to **0.5** micron particle size: **light scattering**) (> **0.16** μg/m^3: **light absorption measurement [density]**)	**0.1** to **0.5** microns (scattering) > **0.16** μg/m^3 (absorption)	No information available	No information available	**Accuracy:** +/- 5-10% relative to calibrating aerosol	Hand-held	No information available

Integrating Sensors into Current Air Pollution Monitoring Paradigm

The FEM 40 CFR Part 53 evaluation protocol is used to assess new technologies considered for use in the US air monitoring network, therefore sensors could be characterized using this approach. The current 40 CFR Part 53 defines: **1)** requirements for determining reference and equivalent methods; **2)** the application process for submitting reference and equivalent method candidates [including witnessing of tests, decision appeals, etc.]; **3)** test procedures for automated systems [SO_2, CO, O_3, NO_2]; **4)** test procedures for lead [Pb]; **5)** test procedures for PM including PM_{10} (Pb), PM_{10}, $PM_{2.5}$ (Class I/II/III), $PM_{10-2.5}$ (Class II/III), $PM_{2.5}$ (reference method, Class I equivalent method, Class II equivalent method)]. Class I/II/II instruments measure $PM_{2.5}$ and $PM_{10-2.5}$.

Class I instrument requirements are defined in 40 CFR Part 50 Appendices L and O and address FRM-like devices with minor design changes to the FRM accommodate sequential sampling and multiple filter media for $PM_{2.5}$ measurement. Therefore sensors for $PM_{2.5}$, developed using newer technology, would not qualify for testing, analysis and characterization by their developers under Class I test procedures. Class II instruments represent EPA-approved designs under 40 CFR Part 50 Appendices L and O, which obtain 24-hour integrated filter deposits for gravimetric analysis and differ from FRM requirements through the use of dichotomous samplers, high volume samplers (with size-selective inlets for $PM_{2.5}$), etc., therefore most sensors for $PM_{2.5}$ would not be developer-tested under Class II test procedures. Class III instruments provide 1 hour or less integrated concentration measurements as well as 24 hour measurements. The Class III instrument category was created to encourage development and evaluation of newer technologies for measurement of $PM_{2.5}$ and includes both filter-based and non-filter based (continuous or semi-continuous) instruments.

Sensors developed for measurement of $PM_{2.5}$ would be tested, analyzed, and characterized by their developers under Class III test procedures. Sensors measuring $PM_{2.5}$ being tested under Class III test procedures would need to implement the following testing protocol: a) 2 test campaigns during two different seasons (summer and winter) at a single test location (site 1 – Los Angeles Basin or Central Valley in California); b) an additional winter test campaign at two different sites (site 2 – western US city [e.g., Las Vegas or Phoenix], and site 3 – midwestern city); c) an additional summer test campaign at a single site (site 4 – large city east of the Mississippi River). The selection of these sites includes consideration of: i) $PM_{2.5}$ nitrates, semi-volatile organic pollutants (site 1); ii) windblown dust (site 2); iii) high temperature variation, high nitrates, winter conditions (site 3), and; iv) high sulfate concentrations, and high humidity levels (site 4).

Incorporating New Technology into the Air Pollution Monitoring Network

EPA's experience in adjusting the filter-based $PM_{2.5}$ FRM to incorporate semi-continuous, near-real time (hourly) measurements from Beta-Gauge, Tapered Element Oscillating Microbalance-Filter Dynamic Measurement System (TEOM-FDMS), Class III FEMs for $PM_{2.5}$, provides a template for incorporating new sensor technology into the US air pollution compliance network. Multiple-site field evaluations of semi-continuous $PM_{2.5}$ candidate instruments were performed and results compared with co-located FRM $PM_{2.5}$ instruments. EPA developed statistically valid and defensible testing and acceptance criteria for semi-continuous $PM_{2.5}$ monitors. The instruments were thoroughly evaluated and tested in the laboratory and in the field. It is important to note that beta-gauge and TEOM-FDMS instruments were well-established and widely used prior to EPA's effort to formally incorporate semi-continuous $PM_{2.5}$ monitors into its network. Incorporation of sensors into EPA air pollution compliance networks can apply 'lessons learned' from the Beta-Gauge and TEOM-FDMS experience.

Application and Review Process for Candidate FEMs (and Sensors)

The process for submitting new candidate equivalent methods is described here. Whenever new monitor or analyzer technologies are proposed as equivalent method candidates, the individual or organization sponsoring a new equivalent method(s) must submit their test and operational data through EPA's formal application process. The candidate equivalent method application package(s) for each of the six criteria air pollutants must implement the definitions, analysis, and testing procedures provided in: i) the applicable appendices in **40 CFR Part 50**; ii) **40 CFR Part 53** (**Subpart B [candidate equivalent method: charts/records/test data, calibration, test atmospheres, range, noise, detection limit, interferences, drift, response, precision]** and **Subpart C [comparison: candidate equivalent method to reference method performance]**); iii) **40 CFR Part 53** (**53.2 [a]** and **53.2 [b]**), including **Subpart A**, and **Subpart B**; iv) **40 CFR Part 53** (**53.3 [a]** and **53.3 [b]**), including **Subparts A**, **B**, **C**, **D**, **E**, and **F**. The application package for candidate equivalent methods must demonstrate that all required tests have been completed by the sponsoring individual or organization and that the appropriate test and operational data has been collected for evaluation and subsequent approval decision on method status by EPA. EPA's goal is to work with the sponsoring individual or organization to ensure that the proposed device/instrument is fully characterized before use in compliance monitoring. Application packages for new (candidate) equivalent methods should include as a minimum the elements listed below (**Note:** This is not an exhaustive list and applicants are encouraged to include additional relevant information/items where applicable.):

- User/operator manual;
- Statements addressing:
  - Designation/identification protocol;
  - Measurement range;
  - Compliance (with applicable regulation[s]);
  - Representativeness (of method, sampler, analyzer);
  - Quality control protocol (ensuring all analyzers operate like test article);
  - Durability (expected length of operation under typical operating conditions);
  - Standard adjustments required for test article (if any), and;
  - Statement that test article was not replaced during validation testing for candidate method application;
- Drawings/schematics illustrating component locations, electrical, gas, data/information, and control flows, etc.;
- Calibration data from test, and;
- Test data (see i, ii, iii, and iv above).

Applicants are encouraged to submit questions and requests for test plan approvals in writing. Application packages for candidate equivalent methods should be organized to expedite review. Confidential Business Information (CBI) and proprietary processes, trade secrets, etc., should be clearly and prominently indicated in the application package to protect it from inadvertent disclosure to third parties. Duplicate applications should be sent to the following address(es): Mailing Address - Director, National Exposure Research Laboratory, Process Modeling Research Branch (MD E205-03), United States Environmental Protection Agency, Research Triangle Park, North Carolina 27711; Commercial Delivery (Shipping) Address - Director, National Exposure Research Laboratory, Process Modeling Research Branch (MD E205-03), United States Environmental Protection Agency, 4930 Old Page Road, Durham, NC 27703.

Annually, EPA processes approximately 15 – 25 applications for method designations. EPA reviews all equivalent method applications and sends a response to the applicant within 120 days. If the package is incomplete, or if there are questions on the application, the applicant is required to provide a revised application package. A new 120 day review time period begins with the receipt of a revised application package.

Considerations for Using Sensors in Compliance Monitoring

Characterizing the operational performance of sensors is critical when evaluating them as potential candidates for use in compliance monitoring networks. FEM devices in state, local, and tribal networks have well-established QA/QC procedures, operations and maintenance procedures, organizational structures, and routine auditing to validate and verify performance over time[20]. For sensor devices to be approved as FEMs, they will require the same detailed and consistent sensor calibration procedures, operation manuals, test procedures, firmware programming instructions, and software control and data acquisition setup like other FEMs to ensure reliable operations[15].

Sensors may experience decreased measurement response as a function of service life and/or pollutant loading, therefore testing and analysis characterizing sensor measurement response should occur before using sensors in compliance networks[17]. Air pollution sensors have new and promising capabilities as potential FEMs. Sensors meeting FEM analytical performance specifications including selectivity, sensitivity, interferences, time resolution, measurement precision and accuracy, and data collection capability could be included in EPA's compliance air monitoring network after successful evaluation and approval under 40 CFR Part 53. Issues that must be considered when developing and using sensors as FEMs are provided in Table 3-3 below.

Table 2. Considerations When Using Sensors as FEMs

Issue	**Consideration**	**Rationale/Implication**
1. Measurement Time-Scale may require higher storage capacity	Measurement intervals determine data storage requirements: (e.g., 1-minute, 5-minute, 15-minute, 30-minute, 1-hour, etc.). Measuring data at small time increments increases data volume/storage capacity infrastructure requirements.	Need sufficient data for analysis. Need to consider data/database storage costs and how data will be processed, stored, analyzed, and reported.
2. Measurement performance capabilities, including accuracy and precision, and QA/QC protocols	Compatibility with existing methodology.	Decide how and which sensor measurements in a data set are retained or excluded.
3. Operations/maintenance and/or configuration requirements for sensors	FRM and FEM instruments have regular maintenance/data/filter collection cycles. What are sensors requirements for manpower, resources and/or skills?	Many sensor types require replacement of batteries (1-2 year lifespan) and other consumables. This impact on device turnover, operations, and cost must be considered.

4. Microenvironmental measurements collected from home, school, work, market, ambient air, etc.	Sensors provide a straightforward way to correlate ambient pollutant concentrations to microenvironmental concentrations by comparing outdoor and indoor readings.	Is an inexpensive method for collecting microenvironmental concentration data for use in EPA exposure models.
5. Level of measurement variance[s] between sensors and FRMs for a sensor unit to be considered	Different sensors have different accuracy and precision measurement characteristics, so analysis is required to determine divergence of sensor measurement 'tiers' (https://sites.google.com/site/airsensors2013/final-materials)[16]	Characterize sensors based on measurement accuracy
6. Integration of sensors and their communication protocols to ensure that sensor data is accessible	For sensors used in EPA's (and/or state/local/tribal) network(s), communication protocol[s] can transmit sensor measurements for display.	Sensor benefits: immediate visualization of measurement data; display to public importance of EPA's mission to their health and environment: see EPA project (http://villagegreen.epa.gov/)[21]
7. Procedure for downloading sensor measurements into EPA's compliance monitoring network	Sensor data processing cannot be drastically different from EPA approach (e.g., AQS, AIRNow, etc.) - noted in EPA workshop (https://sites.google.com/site/airsensors2013/final-materials)[16]	If sensor data formats/types are incompatible with current EPA formats, database/data collection upgrades will be required and costs will increase

Potential Impact of Sensors

The existence of low cost sensors, those less than $1,000 (USD) with miniaturized electronics, allows for air pollutant monitoring in more locations and microenvironments. Factors encouraging use of this next generation of air pollution monitoring technology include: **a)** smaller size; **b)** portability; **c)** ability to communicate with different networks (e.g., wireless, Bluetooth, TCP/IP, Ethernet, etc.) – need standard communication protocol; **d)** significantly lower cost than existing monitors/analyzers/samplers; **e)** greater spatial coverage since expensive infrastructure is not required; **f)** generating real-time data that can be linked with human activity and location information for exposure assessment, and ; **g)** potential use in tracking vehicle (fleet) emissions. Performance characteristics of sensors require careful consideration, for example: **1)** How do sensors operate in compliance networks?, and ; **2)** How does the uncertainty or analytical performance of sensors compare to FEMs (e.g., limits of detection, sensitivity/interferents, measurement precision/accuracy, etc.)? These questions would be evaluated per 40 CFR Part 53 (on a device-by-device basis).

Effective Integration of Sensors into Monitoring Networks

The pace of sensor research is rapid and will lead to more available devices at a price and performance point that may place additional demands on EPA to evaluate and validate sensors for use in compliance monitoring. However, EPA has an existing 40 CFR Part 53 process of testing and analysis to qualify new measurement devices for its compliance networks. EPA works to ensure that new monitoring devices of any type, considered for compliance monitoring, has the required specificity, accuracy, precision, minimal interferences, etc., as detailed in 40 CFR Part 53, otherwise those devices cannot be used in a compliance monitoring context.

Current Status and Recommendation

EPA and the states/districts/tribes devote resources to air pollution monitoring under the CAA. If sensors are integrated into EPA compliance networks, the current cost of monitoring could be reduced. Also, sensors could facilitate measurement of other pollutants recently linked to health concerns, for example, black or elemental carbon, ultrafine particles, certain soluble transition metals, and others[22] to provide data for consideration of future NAAQS and/or exposure monitoring. Under 40 CFR Part 53, EPA has a key role in defining performance specifications for these new types of instruments. For example, a protocol for testing interferences for candidate reference and equivalent methods is given in table B-3 of 40 CFR Part 53, which can be applied to sensors.

In implementing 40 CFR Part 53, EPA plays an active role in advancing monitor and analyzer technology and works with sensor researchers[16]. The suggested protocol for including sensors as compliance decision making tools is 40 CFR Part 53, which is the approach being used in the current evaluation of NO_2 and O_3 sensors. These sensors are undergoing the following 'Part 53' evaluation process: **a.** <u>test</u>: laboratory conditions (**<u>complete</u>**); **b.** <u>test</u>: EPA-RTP ambient monitor AIRS field test site (**<u>complete:</u> Aug 2013**); **c.** <u>test</u>: ambient/field/near-road (real-world, non-EPA site) conditions (**<u>Sept 2013:</u>** Houston – sensor evaluation project – '**<u>special study</u>**' to validate performance, collect and analyze data including: linearity [of operating range]; measurement precision/resolution; limits of detection; response time; temperature and relative humidity impacts; interferents, etc.); **d.** <u>field analysis</u>: with collocated FRM/FEM devices in EPA Network for analysis/comparison – to collect data for the new 'sensor' method (**<u>planning stage</u>**). The procedure outlined here (**a.** through **d.** above) serves as a template to evaluate sensors for network use. This process provides a viable path for including sensors in EPA's network which meet or exceed the 40 CFR Part 53 requirements contingent on EPA approval and formal method designation.

Sensor developers should become familiar with the 40 CFR Part 53 requirements to facilitate FEM designations for their instruments. EPA is currently evaluating sensors and is working to create appropriate standard operating procedures and User Manuals, QA/QC procedures for sensor data, sensor calibration procedures, maintenance/repair/replacement procedures, and procedures to characterize interferences, etc. EPA maintains an ongoing dialog with the sensor development community through a series of workshops it sponsors to examine new air pollution monitoring technologies[16].

Summary

The FEM protocol under 40 CFR Part 53 provides a method to evaluate sensors for potential inclusion in EPAs compliance monitoring network. Sensors are positioned at the interface where new technology maps onto EPA's 40 CFR Part 53 technology insertion process. EPA actively works to characterize the performance of these devices, how they can be used, and how to adopt this new monitoring paradigm to serve the needs of the agency and the public[16,17].

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Disclaimer

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