Monitoring for Fine Particulate Matter

Elisa Eiseman

Critical Technologies Institute

RAND

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PREFACE

In accordance with the Clean Air Act, the United States Environmental Protection Agency (EPA) has reviewed the National Ambient Air Quality Standards (NAAQS) for particulate matter (PM) and set new standards for fine particulate matter with a diameter less than or equal to 2.5 μm ($PM_{2.5}$). This document reviews the new Federal Reference Method (FRM) developed by the EPA for monitoring $PM_{2.5}$, which is a manual method that will be used to ensure national consistency in $PM_{2.5}$ monitoring and compliance with the EPA's new standards for PM. This document also describes a number of commercially available monitoring technologies that could be utilized for continuous, real-time monitoring of $PM_{2.5}$. This document should be of interest to the EPA, policymakers, and individuals who need to consider the feasibility of using available monitoring technology for implementing and complying with the updated NAAQS for $PM_{2.5}$. It may also be of interest to national, state and local regulators, who are primarily responsible for ensuring attainment and maintenance of the EPA's ambient air quality standards. The regulated community may also find it helpful to have information about monitoring technologies for $PM_{2.5}$.

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Inquiries regarding CTI or this document may be directed to:

Bruce Don
Director, Critical Technologies Institute
RAND
1333 H St., N.W.
Washington, D.C. 20005
Phone: (202) 296-5000
Web: http://www.rand.org/centers/cti/
Email: cti@rand.org

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SUMMARY

Particulate matter (PM), which includes dust, dirt, smoke, soot, and liquid droplets, comes from a variety of natural and anthropogenic sources and is a mixture of many pollutants made up of several different chemical species. Recent evidence about health effects and the fundamental physical and chemical differences between fine PM (particles 2.5 μm in diameter or smaller) and coarse PM (particles 2.5 to 10 μm in diameter) prompted the EPA to consider separate standards for fine and coarse PM. After a lengthy review of the NAAQS for PM, the EPA set new standards for fine particulate matter with a diameter less than or equal to 2.5 μm ($PM_{2.5}$). In addition to revising the monitoring requirements for coarse PM (PM_{10}), these new standards also established a new FRM for measuring $PM_{2.5}$, new criteria for placement of monitors, new schedules for data collection, and new procedures for ensuring the quality of PM data.

PM monitoring is necessary to provide air quality data to local, state, and national regulatory programs for determining whether an area has attained the new NAAQS. The FRM for $PM_{2.5}$ was developed to assure compliance with the new standards for PM and to ensure national consistency in $PM_{2.5}$ monitoring. However, the FRM is a manual method that is not set up for continuous sampling. Therefore, a need also exists for the development of continuous monitoring technologies for determining PM mass. Several state-of-the-art technologies are commercially available for automated, continuous monitoring of PM mass, including opacity monitors, light-scattering technologies, beta gauges, acoustic-energy monitoring, tapered-element oscillating microbalance (TEOM), and triboelectric technol-

ogy. However, none of these methods has been approved by the EPA, since most of these devices do not directly measure mass.

Furthermore, measuring PM mass alone is not sufficient for source attribution, studies of health and welfare effects, and determination of compliance with standards. It is also important to measure chemical composition. Therefore, a comprehensive approach to PM monitoring requires a combination of analytical techniques to assess mass and chemical composition, and an integrated network of ambient and source PM monitors. However, chemical analysis of PM is costly and difficult, and existing technologies are not capable of continuous sampling and monitoring for chemical composition. Therefore, the next generation of PM monitors should be multifunctional instruments capable of continuous, real-time monitoring of both PM mass and chemical composition. In addition, they will need to address several barriers to their use, including cost, complicated calibration and verification systems, and cumbersome installation and maintenance procedures.

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GLOSSARY

AAS	Atomic absorption spectrometry
AC	Automated colorimetry
CEMS	Continuous emissions monitoring systems
CPM	Continuous Particulate Monitors
EPA	United States Environmental Protection Agency
FRM	Federal Reference Method
GC/MS	Gas chromatography combined with mass spectroscopy
gr/dscf	Grains per dry standard cubic foot
HPLC	High-performance liquid chromatography
IC	Ion chromatography
INAA	Instrumental neutron activation analysis
lidar	Light detection and ranging
NAAQS	National Ambient Air Quality Standards
NO_x	Nitrogen oxides
PIXE	Particle-induced x-ray emission
PM	Particulate matter
PM_{10}	Particulate matter 10 μm in diameter or smaller
$PM_{2.5}$	Particulate matter 2.5 μm in diameter or smaller

ppb	Parts per billion
SO_2	Sulfur dioxide
TEOM	Tapered-element oscillating microbalance
TÜV	German Technical Inspection Agency
VOC	Volatile organic compounds
XRF	X-ray fluorescence

Chapter One

INTRODUCTION

The Clean Air Act, passed by Congress in 1970, requires the U.S. Environmental Protection Agency (EPA) to review the air quality standards periodically for six major air pollutants and incorporate the best available science into these standards to protect the American public from the health hazards of air pollution [1].[1] Recently, the EPA reviewed the current National Ambient Air Quality Standards (NAAQS) for particulate matter (soot) and on July 17, 1997, set new standards for fine particulate matter (PM) with a diameter less than or equal to 2.5 μm ($PM_{2.5}$) [2].[2] These new standards also established a new Federal Reference Method (FRM) for measuring fine particles, new criteria for placement of monitors, new schedules for data collection, and new procedures for insuring the quality of PM data [3].

This report reviews the new NAAQS for PM and the new FRM for determining the mass of $PM_{2.5}$. A number of commercially available monitoring technologies that could be utilized for continuous monitoring of $PM_{2.5}$ are also described. This report also provides a definition of PM and outlines a number of issues inherent in using these technologies for environmental compliance monitoring. The appendixes provide detailed information on the applications, mechanisms of action, and advantages of and barriers to commercialization of specific alternative monitoring technologies.

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[1]The six air pollutants Congress specified in the Clean Air Act are ozone, particulate matter, nitrogen dioxide, carbon dioxide, sulfur dioxide, and lead [1].

[2]Concurrently, the EPA also reviewed the NAAQS for ground-level ozone (smog) and issued new air quality standards for ozone [4].

DEFINITION OF PARTICULATE MATTER

Particulate matter (PM), which includes dust, dirt, smoke, soot, and liquid droplets, comes from a variety of natural and anthropogenic sources and is a mixture of many pollutants made up of several different chemical species. Airborne PM can be divided into two classes, fine PM (particles 2.5 μm in diameter or smaller) and coarse PM (particles 2.5 to 10 μm in diameter), which differ not only in size but may also differ in source, chemical composition, physical properties, and formation process [5].[3] Fine PM ($PM_{2.5}$) is derived mainly from combustion material that has volatilized and then condensed, or from the condensation or transformation of emitted gases in the atmosphere, such as sulfur dioxide (SO_2), nitrogen oxides (NO_x) and volatile organic compounds (VOC) [5]. Major sources of $PM_{2.5}$ are fossil fuel combustion by electric utilities, industry, and motor vehicles; residential fireplaces and wood stoves; vegetation burning; and the smelting or other processing of metals [5]. Examples of natural bioaerosols suspended as $PM_{2.5}$ include bacteria, viruses, and endotoxins. Major components of $PM_{2.5}$ are sulfate, strong acid, ammonium, nitrate, organic compounds, trace elements (including metals), elemental carbon, and water [5]. Coarse PM is formed by crushing, grinding, and abrasion of surfaces, which are then suspended by the wind or by anthropogenic activity [5]. Mining and agricultural activities are examples of anthropogenic sources of coarse PM [5]. Fugitive dust constitutes about 90 percent of estimated coarse PM [5]. Fungal spores, pollen, and plant and insect fragments are examples of natural bioaerosols suspended as coarse PM [5]. Therefore, since fine and coarse PM are derived from distinctly different sources and have different chemical and physical properties, monitoring ambient levels of each would facilitate the planning of effective control strategies.

EPA'S REVISED PARTICULATE MATTER STANDARDS

Recent evidence about health effects and the fundamental physical and chemical differences between fine and coarse PM prompted the

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[3]The terms *fine* and *coarse* originally applied to the two major atmospheric particle distributions, which overlap in the size ranges between 1 and 3μm in diameter[5]. More recently, *fine* has come to be associated with $PM_{2.5}$, and *coarse* often refers to particles 2.5 to 10 μm in diameter ($PM_{10–2.5}$) [5].

EPA to consider separate standards for fine and coarse PM. Previously, the NAAQS for PM required monitoring of particles 10 μm in diameter or smaller (PM_{10}), with the annual average set at 50 $\mu g/m^3$ and the 24-hour average set at 150 $\mu g/m^3$ [6]. However, the NAAQS have been revised to include new standards for particles 2.5 μm or smaller ($PM_{2.5}$), with the annual average set at 15 $\mu g/m^3$ and the 24-hour average set at 65 $\mu g/m^3$ [6]. PM_{10} standards were also revised so that larger, coarse particles will continue to be regulated [6].[4] The new air quality standards were implemented to address the latest scientific information on the effects of $PM_{2.5}$ on public health and welfare.

Since the standards were last revised in 1987, numerous studies have been published on the health effects of PM [7]. New PM-related epidemiological studies have suggested correlations between breathing particles at levels below the previous PM standards and harmful health effects [2, 7]. The PM-related health effects observed in these epidemiological studies included premature mortality, aggravation of respiratory and cardiovascular symptoms and illness, changes in lung structure and function, and altered respiratory defense mechanisms [7]. In addition, children, asthmatics, and individuals with cardiovascular or pulmonary disease, especially the elderly, are more likely to suffer severe health effects related to PM exposure [7]. While both coarse and fine PM can produce health effects, the fine PM, which penetrates deeply and remains in the lungs, is more likely to be linked to the kinds of effects observed in these epidemiological studies [2]. The EPA predicts that the new PM standards, along with clean air programs already planned, would reduce premature deaths by an estimated 15,000 per year and reduce serious respiratory problems in children by approximately 250,000 cases per year [7].

Effects on public welfare associated with ambient airborne PM include visibility impairment, climate change, and materials damage. The major cause of visibility impairment is $PM_{2.5}$, so reducing $PM_{2.5}$ concentrations will improve visibility [5]. Particles suspended in the atmosphere also exert an impact on climate by increasing the reflec-

[4] The EPA retained the annual PM_{10} standard of 50$\mu g/m^3$ and adjusted the 24-hour PM_{10} standard of 150$\mu g/m^3$ by replacing the one-expected-exceedance form with a 99th percentile form, averaged over 3 years [2, 6].

tion of solar radiation from cloud-free portions of the atmosphere and by increasing the brightness and stability of clouds [5]. Damage to materials by PM exposure includes soiling of painted surfaces, fabrics, electronics, and works of art and corrosion of metals and other building materials by acid aerosols and salts [5].

Chapter Two

$PM_{2.5}$ MONITORING

Monitoring is necessary to determine the quality of our nation's air and to assess the progress of control strategies toward achieving ambient air quality goals. Air quality samples are generally collected for one or more of the following purposes [8]:

- To judge when an area has attained and/or made progress toward meeting ambient air quality standards.
- To activate emergency control procedures that prevent or alleviate air pollution episodes.
- To observe pollution trends throughout the region, including non-urban areas.
- To provide a database for research evaluation of effects: determination of health and welfare effects; urban, land-use, and transportation planning; development and evaluation of abatement strategies; and development and validation of diffusion models.
- To provide a baseline for market-based approaches such as emissions trading.

Since regulation requires information, monitoring technologies that provide information on compliance with environmental regulations are essential.

The main purpose of PM monitoring is to provide air quality data to local, state, and national regulatory programs for determining whether an area has attained the NAAQS. To assure compliance with

the new standards for PM, the EPA has developed a new FRM for $PM_{2.5}$. However, the FRM is a manual method designed to measure $PM_{2.5}$ mass and is not set up for continuous sampling or compositional analysis. Therefore, a need also exists for the development of continuous monitoring technologies for determining both PM mass and chemical composition.

FEDERAL REFERENCE METHOD FOR $PM_{2.5}$

To ensure national consistency in air pollution monitoring, a FRM is used for making comparisons to the standards. The FRM for determining the mass of fine particulate matter having an aerodynamic diameter less than or equal to 2.5 μm ($PM_{2.5}$) is a manual method that provides a direct measurement of the mass of ambient $PM_{2.5}$ over a 24-hour period [6]. Briefly, the FRM utilizes an electrically powered air sampler to draw air at a constant rate through an impactor, which is a particle size separator, where suspended $PM_{2.5}$ is separated for collection on a filter (for more information on the FRM air sampler, see Appendix A). The filter is then removed from the sampler, brought back to the laboratory, equilibrated, and weighed to determine the ambient mass concentration of $PM_{2.5}$. This analysis is costly, time consuming, and laborious. The sampling apparatus alone costs approximately $7,000 per unit, and requires extra full time employees for daily sampling, with additional operation and maintenance costs. In addition, the new $PM_{2.5}$ monitoring network will eventually consist of approximately 1,500 sites, with daily sampling required at over 300 of these sites and sampling every third day required at the rest [9].[1] To defray the costs of establishing the $PM_{2.5}$ monitoring network, Congress has appropriated $35.6 million for the State and Tribal Assistance Grant account to be distributed as EPA grants for "particulate matter monitoring and data collection" [10].

Over the long term, there is a need for PM monitoring technologies that are continuous and automatic and that provide real-time analysis. To ensure that new, improved monitoring technologies are

[1]The $PM_{2.5}$ network will initially consist of a minimum of approximately 850 required $PM_{2.5}$ monitoring sites, while the mature network is projected to consist of 1,500 $PM_{2.5}$ sites within three years [9].

incorporated into the monitoring network, three classes of equivalent methods are established in the specifications for the FRM [3, 6, 9]. Class I equivalent methods include minor sampler modifications to allow the automatic collection of sequential samples without intermediate operator service, permitting easier and more cost efficient sampling on a daily basis. Class II equivalent methods include all other filter-based methods that produce a 24-hour measurement. Finally, Class III equivalent methods include both continuous or semicontinuous methods that are based on designs and measurement principles different from the reference method. However, there may be significant problems in translating from the manual reference method to a continuous one. In addition, the guidelines for the FRM are so strict that they may dictate adherence to a single method, thereby inhibiting innovation.

ISSUES REGARDING THE USE OF THE $PM_{2.5}$ FEDERAL REFERENCE METHOD (FRM)

Time to Results

The standard operating procedure for the new $PM_{2.5}$ FRM defines the time line for sampling and analysis of ambient PM [6] (Figure 1). Briefly, the $PM_{2.5}$ sample is collected for 23–25 hours. The filter must be retrieved from the sampler within 96 hours (4 days) of the end of the sample collection period. After retrieval from the sampler, the filter containing the $PM_{2.5}$ sample is transported to the laboratory, ideally within 24 hours, for conditioning and equilibration and subsequent weighing. The filter is equilibrated for a minimum of 24 hours. The postsampling weighing occurs immediately after the filter is conditioned. If the filter is retrieved for conditioning immediately after the sampling period, the minimum time from the beginning of sample collection to the report of results would be 47 hours (approximately 2 days). The stipulation that the postsampling equilibration and weighing be completed within 240 hours (10 days) gives a maximum of approximately 11 days from start to finish. Since acute PM exposures (exposures of less than 1 day to up to 5 days) are associated with an increased daily mortality, usually occurring either on the same day or within one day after exposure [5], these time lags between sample collection and measurement of $PM_{2.5}$ mass would

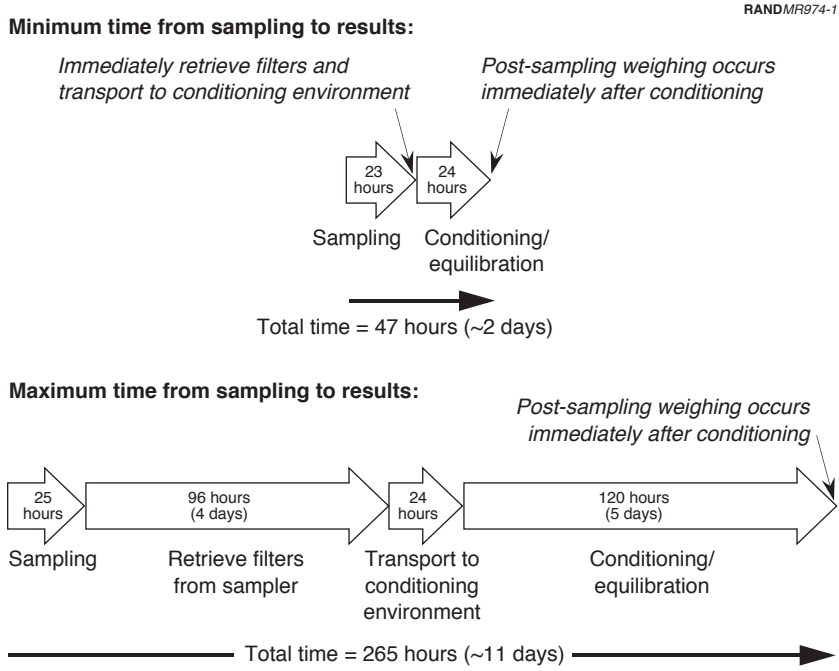


Figure 1—Sampling Time Line for the FRM. The sampling time line for the FRM illustrates the minimum and maximum time from sampling to measurement of $PM_{2.5}$ mass. Chemical analysis of $PM_{2.5}$ composition would require additional time and is not depicted in this figure.

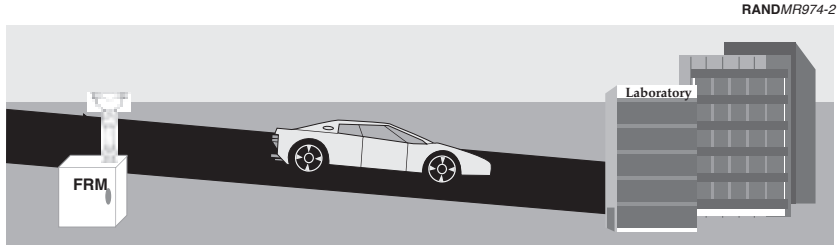
not provide the general public with timely warnings about episodic air pollution hazards. In addition, since the FRM uses a 24 hour batch sample, it would be difficult to correlate data with meteorological events or other time-sensitive emission sources that may last only minutes to hours, such as when there are heavy traffic flows, increased industrial activities, and periods of high energy demand.

Accuracy and Precision

The EPA's standard for $PM_{2.5}$ requires high-quality data, with minimal imprecision and relative error. The EPA's quality assurance goal for $PM_{2.5}$ measurements is defined as within ±15 percent [6]. However, there is significant error associated with the $PM_{2.5}$ FRM. For

example, substantial errors of 50 percent or more have been observed when using different measurement techniques; samplers of different design or manufacturer; or even identical systems of different age, cleanliness, or placement [5]. It is possible to obtain measurements with a precision close to 10 percent when using collocated samplers of identical design and cleanliness [5]. Therefore, the calibration of equivalent methods with the FRM may be quite difficult and will be of utmost importance to ensure consistency and compliance with national standards.

The errors in $PM_{2.5}$ measurements may arise during sampling, transport of the sample to the laboratory, and/or at the laboratory (see Figure 2). One of the main sources of sampling error is the loss of



Sampler error

- Loss of semivolatile components
- Ambient temperature <–30˚C (–22˚F) or >45˚C (113˚F)
- Filter temperature >3˚C above ambient temperature
- Adverse weather conditions
- Sampler malfunction
- Sampler design
- Sampler age and cleanliness
- Sampler leakage
- Flow rate and sampling time

Transport error

- Temperature >32˚C (90˚F)
- Humidity
- Removal of filter from sampler
- Protective container failure
- Transportation time
- Handling and storage

Laboratory error

- Conditioning/equilibration
  - Variations of mean temperature from 20-30˚C (68-73˚F) ± 2˚C
  - Variations of mean humidity from 30-40% ± 5%
  - Time <24 hours
- Pre- and post-sampling filter weighing
- Handling and storage

Figure 2—Sources of Error. The EPA's precision goal for $PM_{2.5}$ measurements is ±15 percent. However, collocated samplers have shown errors of ≥50 percent due to sample, transport and/or laboratory error.

semivolatile components, such as certain organics and nitrates, through evaporation and sublimation during variable temperature and humidity conditions. To reduce the loss of semivolatile components of $PM_{2.5}$, the proposed FRM limits the temperature rise of the sample filter to 3°C above ambient temperature during sampling, as well as after sample collection while the sample is retained in the sampler awaiting retrieval [6]. However, sampler operational conditions define the ambient temperature range from –30°C (–22°F) to 45°C (113°F) and ambient humidity as 0 to 100 percent [6]. These extremely broad operational conditions may effect sample condensation or volatilization, making comparisons of data difficult across the entire country, especially in places with such diverse climates as Phoenix, Arizona, and Nome, Alaska. Furthermore, temperatures in such locations as these may routinely rise above or fall below the ambient limits set by the EPA. Since samples are collected over a 24-hour period and are stored in the sampler for up to 96 additional hours, daily variations in ambient temperature may also affect sample integrity at individual monitoring sites. In addition, seasonal weather variations may introduce sampling errors at individual monitoring sites. Significant sampling error may also be introduced by sampler malfunction or leakage, the age or cleanliness of the sampler, sampler design, and/or sampling time and flow rate. Additional error may be introduced during transport of the sample from the sampler to the laboratory due to handling and storage of the sample during transport, temperature and humidity fluctuations, and/or failure of the protective container that holds the sample during transport. Finally, significant error may be introduced at the laboratory during the conditioning, equilibration, weighing, and/or handling and storage of the sample. This high level of error in $PM_{2.5}$ measurements may increase public health risks when measurements underestimate true concentrations or may cause unnecessary control requirements when the true concentrations are overestimated.

Source Attribution

Compositional analysis is very important for the identification of $PM_{2.5}$ emission sources and the development of effective control programs. Because of the costs associated with conducting compositional analysis on a routine basis, the FRM only requires archiving of filters collected for $PM_{2.5}$ mass measurement so they are available

for analysis on an as-needed basis. Since the chemical analyses are usually conducted long after the samples are collected on filters, there is a risk of losing semivolatile compounds due to adsorption, volatilization, or degradation during handling and storage. This may pose significant problems for developing control strategies and for source attribution in areas where semivolatile PM is abundant. Such losses may be very important in areas affected by wood smoke for organic compounds or in agricultural areas, where there are high levels of ammonia. Therefore, as part of the overall PM monitoring program, the EPA has incorporated special-purpose monitors, which use alternative samplers and supplemental analyzers, to help characterize the chemical composition of PM [3].

CONTINUOUS $PM_{2.5}$ MONITORS

Several state-of-the-art technologies are commercially available for automated, continuous monitoring of PM mass, ranging in price from $10,000 to $35,000. These include opacity monitors, light-scattering technologies, beta gauges, acoustic-energy monitoring, tapered-element oscillating microbalance (TEOM), and triboelectric technology (for additional information on these and other monitoring technologies see Appendixes A and B and Reference 11):

- **Opacity monitors** measure the degree to which PM reduces the transmission of light. Several types of opacity monitors are commercially available: (1) the Aethalometer™ is a type of opacity monitor used for ambient monitoring of suspended particles, such as black carbon from combustion of fossil fuels; and (2) Continuous Particulate Monitors (CPM) are variants of opacity meters used for stack sampling of PM emissions and for monitoring filter-bag bleedthrough, leaks, and broken-bag failures.
- **Light-scattering technologies** provide an indirect measurement of fine PM concentrations by utilizing the relationship between particle concentration and light scattering. Light-scattering technologies, which include forward scattering, backscattering, and 90-degree (side) scattering technologies, can be used for *in situ*, continuous stack sampling and/or ambient air monitoring of PM emissions. For example, (1) Nephelometers measure the visual quality of local ambient air by measuring the scattering of

light due to particles in continuous air samples; (2) light detection and ranging (lidar) is used for remote detection of the presence, velocity, and chemical makeup of "particles" ranging from aircraft and missiles to smoke, dust, and "invisible" gases by measuring backscattered light; and (3) side-scattering technologies, which have been approved by the German equivalent of the EPA, are installed on 100 to 200 stacks.

- The **beta gauge**, which uses a radioactive source and measures the attenuation of radiation through an exposed filter, can be used for stack sampling of PM emissions.
- **Acoustic energy monitoring**, which measures particle loading by measuring shock waves caused by the impact of particles with a probe inserted into the flow, is used for *in situ*, continuous stack sampling of PM emissions.
- **TEOM** directly measures PM mass by measuring the changing frequency of oscillation of a filter as it accumulates particles. TEOM is used for ambient PM monitoring.
- **Triboelectric technology**, which relies on a form of contact electrification, measures the electric current induced by particles as they flow past and hit a metal probe. Triboelectric technology is used for stack sampling of PM emissions and monitoring of flow upsets and bag breakthroughs.

These continuous emission monitoring systems (CEMS) for PM are automated and provide continuous, real-time data, all of which are distinct advantages over the manual FRM (see Figure 3). However, the FRM provides a direct measure of mass and is not sensitive to particle size, density, or color, which are characteristics most of the PM CEMS cannot provide.

ISSUES REGARDING THE USE OF CONTINUOUS $PM_{2.5}$ MONITORS

Inferred Mass Measurements

None of the continuous $PM_{2.5}$ monitors described above have received EPA approval for PM mass monitoring. This is probably due to the fact that most of these devices do not make direct measure-

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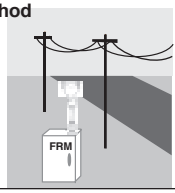
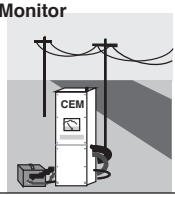
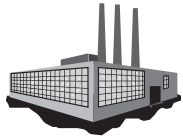
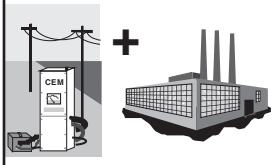
PM Monitor	Advantages	Disadvantages
Federal Reference Method 	• Detects mobile sources • Detects fugitive emissions • Direct measure of mass • Not sensitive to particle size, density, and color	• Manual method • Not continuous • Not real-time • Loss of semivolatile components • Time consuming • Laborious • Costly
Continuous Ambient PM Monitor 	• Detects mobile sources • Detects fugitive emissions • Continuous • Real-time • Automated	• No direct measure of mass • No source attribution • Requires site-specific calibration • Sensitive to particle size, density, and color • Loss of semivolatile components
Continuous Source PM Monitor 	• Detects spikes • Process feedback • Source attribution • Continuous • Real-time • Automated	• No direct measure of mass • Miss fugitive emissions • Miss mobile sources • Requires site-specific calibration • Sensitive to particle size, density, and color • Loss of semivolatile components
Ambient and Source PM Network 	• Detects mobile and stationary sources • Detects spikes and fugitive emissions • Source attribution • Process feedback • Continuous • Real-time • Automated	• No direct measure of mass • Requires site-specific calibration • Sensitive to particle size, density, and color • Loss of semivolatile components

Figure 3—PM Monitors

ments of mass but instead measure secondary properties of particles from which the mass must be inferred. Therefore, existing devices must be calibrated against a manual reference method.

Since many of these technologies are sensitive to changes in flow velocity, temperature, particle size distribution, and particle properties, they require site specific calibration in order to make PM mass measurements. Currently, there is no way to verify economically and frequently whether calibration curves are stable with time or are sensitive to changes in particle size, density, or color. The only device that directly measures mass is the TEOM; however, it is sensitive to humidity and temperature and requires periodic filter changes that result in downtimes of one-half hour to two hours after each filter change.

Particle Sizing

Existing technologies use inertial impactors or dichotomous samplers as particle size separators that only approximate PM size. Dichotomous samplers provide concentration data for PM_{10} and $PM_{2.5}$ by separating particles by acceleration through a nozzle and collection of fine particles at 90 degrees to the flow. Inertial impactors provide information on multiple size fractions by collecting particles on filters or an impaction surface by drawing air through a series of converging nozzles. Large particles have higher inertia and are collected first, while smaller particles are collected in later impaction stages. For both of these technologies, sizing is based on the aerodynamic properties of the particles and the diameter of a unit density sphere. However, these properties of PM vary significantly (e.g., diesel PM is very long; soil can be crystalline; and pollen is very rough and lightweight). Therefore, particles that are larger and lighter than the reference sphere may get through, while some smaller, heavier particles may be selected out and lost.

Chemical Composition

Monitoring of both PM mass and chemical composition is important for identification of emission sources, determination of compliance, and development of effective control programs. However, chemical analysis of the organic fraction of airborne PM is very costly and dif-

ficult because of the complex mixture of hundreds of compounds. Currently, analyses of organic compounds are performed in a laboratory setting using high-performance liquid chromatography (HPLC) and gas chromatography combined with mass spectroscopy (GC/MS), but these technologies can only identify 10 percent to 20 percent of the chemical compounds in the sample [5]. Metals and other elements are analyzed using x-ray fluorescence (XRF), particle-induced x-ray emission (PIXE), and instrumental neutron activation analysis (INAA) [5]. Atomic absorption spectrometry (AAS) is used for soluble ions, such as sodium, magnesium, potassium, and calcium. Ion chromatography (IC) is used for nitrate and sulfate [5]. Automated colorimetry (AC) is used to measure ammonium, chloride, nitrate, and sulfate [5]. Collection and measurement technologies for elemental and organic carbon are not as well established [5]. Only highly experimental instruments exist that can first collect a PM sample and then perform compositional analysis [12]. There is nothing that is ready for routine use. Until these multifunctional instruments are available for routine use, samples must be collected and then brought back to a lab for analysis, which is very expensive and time consuming. Existing technologies for sampling PM are not set up to run continuously or to collect multiple samples on multiple days. In addition, sampling artifacts can cause significant errors in measurement of organic PM. There is a risk of losing semivolatile organic compounds and semivolatile ammonium compounds due to adsorption, volatilization, or degradation during sampling or to storing the sample in the instrument or at the laboratory for extended lengths of time.

Chapter Three

CONCLUSIONS

There are advantages and disadvantages to using PM CEMS for ambient monitoring and source sampling (see Figure 3). PM CEMS are automated and provide continuous, real-time data, but cannot directly measure mass; are sensitive to particle size, density, and color; and require site-specific calibration. In contrast, the FRM does provide a direct measure of mass and is not sensitive to particle characteristics, but it is a manual method that cannot provide continuous, real-time data, and it is costly, time consuming, and laborious. Ambient PM monitors detect emissions from mobile sources and fugitive emissions that would be missed by source PM monitors, while source PM monitors detect spikes and provide source attribution and process feedback. Furthermore, measuring the chemical composition of PM is also necessary for source attribution. Therefore, the ideal system would be an integrated network of ambient and source PM CEMS that, in addition to providing continuous, real-time data, would also provide source attribution, detect emissions from both mobile and stationary sources, detect spikes and fugitive emissions, and assess chemical composition.

Appendix A

AIR MONITORING TECHNOLOGIES FOR PARTICULATE MATTER

Appendix A provides detailed information about the Federal Reference Method for fine particulate matter (FRM $PM_{2.5}$). Information is also provided about continuous $PM_{2.5}$ monitors capable of ambient monitoring, stack sampling, or both ambient and source monitoring. Some of the technologies, such as the Aethalometer™, have mainly been used for research; others, such as side-scattering technologies, are installed on over 100 stacks.

FEDERAL REFERENCE METHOD FOR FINE PARTICULATE MATTER (FRM $PM_{2.5}$) SAMPLER [6, 13]

Applications: The FRM $PM_{2.5}$ Air Sampler is an advanced manual method for performing $PM_{2.5}$ measurements. This sampler was designed to meet the monitoring requirements of the new EPA reference method for monitoring $PM_{2.5}$.

Example: The Partisol-FRM Plus Air Sampling System is a class I equivalent method for $PM_{2.5}$ sampling that uses exchangeable sampling modules. It can be configured with a single-filter sampling module to meet the new EPA $PM_{2.5}$ reference method, or as a class I equivalent method with a five-filter sampling module.

Existing/Near Term (2–4 years)/Far Term (≥5 years): The FRM $PM_{2.5}$ Air Sampler was developed from the PM_{10} manual reference method used by the EPA.

Mechanism of Action: The FRM $PM_{2.5}$ Air Sampler utilizes an electrically powered air sampler to draw air at a constant rate through an

impactor, which is a particle size separator, where suspended $PM_{2.5}$ is separated for collection on a filter. The filter is then removed from the sampler, brought back to the laboratory, equilibrated, and weighed to determine the mass of $PM_{2.5}$.

Platform: The FRM $PM_{2.5}$ Air Sampler is used for ambient monitoring of PM having an aerodynamic diameter less than or equal to 2.5 μm ($PM_{2.5}$).

Chemicals/Pollutants Detected: The FRM $PM_{2.5}$ Air Sampler is used to monitor $PM_{2.5}$, such as dust, dirt, soot, smoke, and aerosols (liquid droplets).

Accuracy/Reliability/Thresholds: Significant error is associated with the FRM $PM_{2.5}$ Air Sampler, which may arise during sampling, transport of the sample to the laboratory, and/or at the laboratory. One of the main sources of sampling error is the loss of semivolatile components, such as certain organics and nitrates, through evaporation and sublimation during variable temperature and humidity conditions.

Data Collection, Availability, and Processing Requirements: The filter must be removed from the sampler, brought back to the laboratory, equilibrated, and weighed to determine the mass of $PM_{2.5}$.

Advantages: The FRM $PM_{2.5}$ Air Sampler provides a direct measure of PM mass. It is not sensitive to particle size, density, or color and is highly reliable in ambient conditions ranging from –45 to +45°C, as well as in areas with high humidity conditions.

Disadvantages: The FRM $PM_{2.5}$ Air Sampler is a manual method that cannot provide continuous, real-time data. It is time consuming, laborious, and costly.

Cost: The Partisol-FRM Plus Air Sampling System is commercially available for approximately $7,000.

OPACITY MONITORS [14, 15]

Applications: Opacity monitoring has been used for compliance purposes in continuous monitoring situations. However, in these instances, only opacity is being measured and not actual PM emissions.

Examples:

1. The Aethalometer™ measures ambient pollutant species of suspended carbonaceous particles, which are a ubiquitous component of traffic and industrial combustion emissions. (See Appendix B, p. 33.)
2. Continuous Particulate Monitors (CPM) are variants of opacity meters used for stack sampling of PM emissions and monitoring filter-bag bleedthrough, leaks, and broken-bag failures. (See Appendix B, p. 36.)

Existing/Near Term (2–4 years)/Far Term (≥5 years): Opacity monitors are an existing technology available for ambient monitoring and stack sampling of PM.

Mechanism of Action: Opacity monitors represent the simplest optical approach to the measurement of particulate matter (PM). Opacity is defined as the degree to which particles reduce the transmission of light. Technology to monitor opacity is based on determining the amount of light absorbed and scattered when a light signal of known intensity is passed through a gas stream. The traditional method is to measure light extinction, or loss of light, by measuring the degree to which emissions or dust flow reduce the transfer of light. Extinction is dependent on both the composition and size of the particles and is typically referred to as opacity. The relative level of dust is calculated by:

$$\text{Transmission T} = \text{Received Light}/\text{Transmitted Light}$$

and

$$\text{Optical Density (Opacity)} = \text{LOG } 1/T$$

Platform: Conventional opacity devices have been used for ambient monitoring, as well as continuous monitoring of stack emissions.

Chemicals/Pollutants Detected: Opacity devices are used to monitor PM, such as dust, dirt, soot, smoke, and aerosols (liquid droplets).

Accuracy/Reliability/Thresholds: Opacity monitors have a typical range of applicability of 0.02 to 4 gr/dscf.

Data Collection, Availability, and Processing Requirements: Opacity monitors do not measure mass and must be calibrated against the EPA's FRM. The FRM involves isokinetic sampling and collection of particles on a filter, which is then weighed to determine the mass of PM. The FRM is a manual method and involves time-consuming analysis that provides a direct measurement of the mass of PM.

Advantages: Opacity monitors are an established technology and operate reliably.

Disadvantages: Opacity monitors are the least sensitive of the various optical approaches to monitoring PM. This is due to the fact that a small change in the transmission of light is being measured in a large quantity of emission. Studies have shown that opacity can be correlated with mass emissions; however, concern about the stability of the correlation has prevented the use of opacity for the monitoring of PM mass emissions in the United States.

Installing opacity devices as dust monitors is difficult, since the positioning of the sensors is critical in ensuring accurate and reliable readings. Opacity monitors work well only under ideal operating conditions. They are subject to dirty lenses and alignment problems. Several common conditions will result in inaccurate readings, such as appreciable alteration in particle size distribution or optical properties, vibration, duct flexing and sensor movement caused by temperature changes, fluctuation in the output of the source lamp, and dispersion of the light by dust buildup on the sensors. To overcome these problems, complicated electromechanical devices are used to rezero and respan the instrument over a given period. However, the systems must then be constantly maintained, and daily or hourly recalibrations are often necessary.

Cost: Opacity monitors range in price from approximately $10,000 to $15,000.

LIGHT-SCATTERING TECHNOLOGIES [15]

Applications: Light-scattering technologies can be used for *in situ*, continuous stack sampling and/or ambient air monitoring of PM emissions.

Examples:

1. Nephelometers measure the visual quality of local ambient air by measuring the scattering of light due to particles in continuous air samples. (See Appendix B, p. 38.)
2. Light detection and ranging (lidar) is used for remote detection of the presence, velocity and chemical makeup of "particles" ranging from aircraft and missiles to smoke, dust and "invisible" gases by measuring backscattered light. (See Appendix B, p. 40.)

Existing/Near Term (2–4 years)/Far Term (≥5 years): Several different light-scattering technologies are commercially available. These include forward scattering, backscattering, and 90-degree (side) scattering technologies. Side-scattering technologies have been approved by the German equivalent of the EPA, have passed the German TÜV (Technical Inspection Agency) standards, and are installed on between 100 and 200 stacks.

Mechanism of Action: Light-scattering technologies employ forward-, back-, and side-scattering techniques to monitor particle loading by measuring the scattering of light in addition to the transmitted intensity. The measurement is directly related to the volume of PM present, although in general, it also depends on the PM size distribution and composition. The resultant volume measurement must then be related to mass by assuming a particle density. This is typically accomplished using a site-specific calibration against the EPA's FRM. Inherent in this approach is the assumption that the relation between the measured response and PM mass loading does not change with time.

Forward light scattering is measured by inserting an optical probe into the flow and measuring the light scattered forward from particles passing through a slot in the probe. The measured scattering is used to calculate an average particle size independent of knowledge of the particle size distribution. Combined with the extinction mea-

surement, total particle volume can be calculated. To obtain particle mass, the technique must be calibrated against the EPA's FRM. Insertion of a probe requires only one point of access to the stack.

Backward light scattering is measured by instruments that make use of backscattered light. Insertion of a probe only requires one point of access to the stack. To obtain particle mass, the technique must be calibrated against the EPA's FRM.

Side-scattering technologies are based on instruments that measure light scattering at 90 degrees. Side-scattering devices only require one point of access to the stack. To obtain particle mass, the technique must be calibrated against the EPA's FRM.

Platform: Light-scattering technologies are used for stack sampling and/or ambient air monitoring.

Chemicals/Pollutants Detected: Light-scattering technologies are used to monitor PM, such as dust, dirt, soot, smoke, and aerosols (liquid droplets).

Accuracy/Reliability/Thresholds: Forward light-scattering technologies can detect particles ranging in size from submicrometer to 20 μm. The detection limits for forward light-scattering technologies range from approximately 0.006 gr/dscf to greater than 1 gr/dscf.

Backward light-scattering technologies can detect particles ranging in size from 0.1 to 10 μm. The detection limits for backward light-scattering technologies range from 0.0005 gr/dscf to 8 gr/dscf.

Side-scattering technologies can detect particles ranging in size from 0.1 to 50 μm and have a PM detection limit of $2x10^{-6}$ gr/dscf.

Data Collection, Availability, and Processing Requirements: Light-scattering technologies do not measure mass and must be calibrated against the EPA's FRM. The FRM involves isokinetic sampling and collection of particles on a filter, which is then weighed to determine the mass of PM. The FRM is a manual method and involves time-consuming analysis that provides a direct measurement of the mass of PM.

Advantages: As compared to other optical methods, forward light scattering has reduced sensitivity to particle distribution and characteristics.

Backward light scattering is a sensitive technique for measuring PM and is not dependent on the optical properties of the particles. It is sensitive to particles as small as 0.1 μm.

Side-scattering technologies have excellent sensitivity and are capable of detecting particles as small as 0.1 μm. Side-scattering technologies have been approved by the German equivalent of the EPA and have passed the German TÜV standards. Side-scattering technologies have been installed on between 100 and 200 stacks.

Disadvantages: Forward light scattering displays some sensitivity to particle distribution and particle characteristics, especially if the particle size falls outside the 1 to 20 μm range. In general, it is less sensitive than other light-scattering approaches. Finally, forward light-scattering technologies do not measure mass and must be calibrated against the EPA's FRM.

Backward light scattering displays some sensitivity to particle distribution and particle characteristics, especially if the particle size falls outside the 0.1 to 10 μm range. In addition, backward light-scattering technologies do not measure mass and must be calibrated against the EPA's FRM.

Side-scattering technologies are likely to be sensitive to particle size distribution and particle properties and require site-specific calibration to make PM measurements. Side-scattering technologies do not measure mass; therefore, site-specific calibration against the EPA's FRM is required in each case to provide PM mass emissions.

Cost: Light-scattering technologies range in price from approximately $10,000 for backscattering instruments to approximately $30,000 for forward-scattering instruments.

BETA GAUGE [15, 16]

Applications: The beta gauge uses beta transmissivity for stack sampling of PM emissions.

Existing/Near Term (2–4 years)/Far Term (≥5 years): The beta gauge is an existing technology and is commercially available.

Mechanism of Action: The beta gauge uses a heated sampling probe to obtain an isokinetic sample. The sample is collected on a filter, which, at the end of the sampling period, is moved, using a continuous filter tape mechanism, to a measurement location between a carbon-14 beta particle source and a detector. The beta gauge uses the carbon-14 radioactive source and measures the attenuation of radiation through the filter containing the sample. The beta transmission through each blank filter is determined before sampling begins. The sampling duration is programmable and determines the mass concentration detection limit. At high PM loading, it must be kept small enough to prevent sampling excessive amounts of PM and is usually set at 2 minutes for typical applications. Analysis takes 6 minutes. At the end of each sampling period, the probe nozzle is temporarily closed, opened, and closed again to reentrain any particles that may have deposited in the probe.

Platform: The beta gauge is used for stack sampling of PM emissions.

Chemicals/Pollutants Detected: The beta gauge is used to monitor PM, such as dust, dirt, soot, smoke, and aerosols (liquid droplets).

Accuracy/Reliability/Thresholds: The beta gauge is sensitive to all particles with a detection limit of 1.7×10^{-6} gr/dscf for a 1-hour sample.

Data Collection, Availability, and Processing Requirements: Isokinetic sampling by the beta gauge is maintained automatically. On average, samples are collected for 2 minutes, with analysis of these batched samples taking 6 minutes.

The beta gauge does not measure mass and must be calibrated against the EPA's FRM. The FRM involves isokinetic sampling and collection of particles on a filter, which is then weighed to determine the mass of PM. The FRM is a manual method and involves time-

consuming analysis that provides a direct measurement of the mass of PM.

Advantages: The beta gauge is sensitive to all particles.

Disadvantages: The beta gauge performs batch sampling and is not capable of continuous sampling. There are also problems with accumulation of PM on the probe.

Cost: The beta gauge is commercially available for approximately $35,000.

ACOUSTIC-ENERGY MONITORING [15]

Applications: Acoustic-energy monitoring is used for *in situ*, continuous stack sampling of PM emissions.

Existing/Near Term (2–4 years)/Far Term (≥5 years): Acoustic-energy monitoring is commercially available.

Mechanism of Action: In acoustic-energy monitoring, shock waves caused by the impact of particles with a probe inserted into the flow are used to measure particle loading. These devices count the number of impacts and also measure the energy of each impact. This information, coupled with knowledge of the flow velocity, allows calculation of the particle mass.

Platform: Acoustic-energy monitoring is used for stack sampling of PM emissions.

Chemicals/Pollutants Detected: Acoustic-energy monitoring is used to monitor PM, such as dust, dirt, soot, smoke, and aerosols (liquid droplets).

Accuracy/Reliability/Thresholds: Acoustic-energy monitoring has a range of approximately 0 to 0.05 gr/dscf.

Data Collection, Availability, and Processing Requirements: Acoustic-energy monitoring does not measure mass and must be calibrated against the EPA's FRM. The FRM involves isokinetic sampling and collection of particles on a filter, which is then weighed to determine the mass of PM. The FRM is a manual method and involves time-consuming analysis that provides a direct measurement of the mass of PM.

Advantages: Acoustic-energy monitoring has good sensitivity with a range of approximately 0 to 0.05 gr/dscf.

Disadvantages: Acoustic-energy monitoring is not sensitive to particles smaller than 10 μm. Also, since the probe distorts the flow, changes in flow velocity and particle size distribution will change the instrument response. Acoustic-energy monitoring does not measure mass and must be calibrated against the EPA's FRM.

Cost: Acoustic-energy monitoring devices are commercially available for approximately $12,000.

TAPERED-ELEMENT OSCILLATING MICROBALANCE (TEOM) [13, 15]

Applications: TEOM is designed for ambient air monitoring of PM and is probably not suitable for application to stack sampling.

Existing/Near Term (2–4 years)/Far Term (≥5 years): TEOM is commercially available.

Mechanism of Action: The TEOM acts like a tuning fork, so if the mass of the tapered element is increased, its resonant frequency decreases. Conversely, if the mass of the element decreases, the system measures a corresponding increase in frequency. Attached to the free end of the element is a disposable filter cartridge. As particulate-laden gas passes through the filter, the particles become trapped, causing the mass of the tapered element–filter combination to increase. The cleaned gas stream passes down the hollow element and out to an electronic flow-control system and vacuum pump. A frequency sensor associated with the tapered element sends information to a microprocessor, where the instrument converts the raw signal to a mass measurement. Thus, TEOM is a direct measurement of particle mass.

Platform: TEOM is designed for ambient air monitoring.

Chemicals/Pollutants Detected: TEOM is used to monitor PM, such as dust, dirt, soot, smoke, and aerosols (liquid droplets) from sources including motor vehicle exhaust, residential wood combustion, paved road dust and entrained geological material, coal-fired boilers at power plants, and restaurant grills and residential cooking.

Accuracy/Reliability/Thresholds: Tapered-element technology enables highly precise and accurate mass determinations, providing more resolution than conventional microbalances.

Data Collection, Availability, and Processing Requirements: TEOM directly measures particle mass. The TEOM mass transducer does not require recalibration because it is specially designed and constructed from nonfatiguing materials. Calibration may be verified, however, using a filter of known mass.

Advantages: TEOM provides a direct measurement of mass. It has excellent sensitivity and is sensitive to all particles.

Disadvantages: TEOM is sensitive to humidity and temperature, requiring control of these two parameters. The filter also requires periodic changing, resulting in a one-half to two-hour downtime after each filter change. It is questionable whether TEOM could be made suitable for continuous stack monitoring.

Cost: The TEOM is commercially available for approximately $17,000.

TRIBOELECTRIC TECHNOLOGY [14, 15]

Applications: Triboelectric technology is used for monitoring flow upsets and bag breakthroughs.

Existing/Near Term (2–4 years)/Far Term (≥5 years): This technology is currently available for monitoring flow upsets and bag breakthroughs.

Mechanism of Action: Triboelectric technology relies on a form of contact electrification, which is the phenomenon of two materials being brought together and separated with a charge taking place. Placing a metal sensor probe in the area to be monitored and measuring the electric current induced by the particles as they flow past and hit the metal rod allows this effect to be observed and used as a relative monitoring signal. The magnitude of the effect is dependent on composition, size, flow velocity (i.e., small particles follow streamlines and do not impact the probe), and resistivity (which is highly dependent on humidity). Response is also sensitive to conditioning of the probe surface through the buildup of deposits and/or erosion.

Platform: Triboelectric technology is available for stack sampling.

Chemicals/Pollutants Detected: Triboelectric technology is used to monitor PM, such as dust, dirt, soot, smoke, and aerosols (liquid droplets).

Accuracy/Reliability/Thresholds: Triboelectric technology has a detection limit of $5x10^{-5}$ gr/dscf.

Data Collection, Availability, and Processing Requirements: Triboelectric technology does not measure mass and must be calibrated against the EPA's FRM. The FRM involves isokinetic sampling and collection of particles on a filter, which is then weighed to determine the mass of PM. The FRM is a manual method and involves time-consuming analysis that provides a direct measurement of the mass of PM.

Advantages: Triboelectric technology can be used *in situ* for continuous monitoring. In addition, it can detect particles as small as 0.5 μm, and has excellent sensitivity.

Disadvantages: Triboelectric technology is sensitive to flow velocity, particle size distribution, and particle characteristics. In addition, it is very sensitive to changes in humidity. Triboelectric technology does not measure mass and must be calibrated against the EPA's FRM.

Cost: Triboelectric technology is commercially available for approximately $10,000.

Appendix B

EXAMPLES OF AIR MONITORING TECHNOLOGIES FOR PARTICULATE MATTER

AETHALOMETER™ [12, 17]

Applications: The Aethalometer™ gives a real-time measurement of the concentration of an aerosol component that is specific for combustion emissions. It measures pollutant species of suspended carbonaceous particles, which are a ubiquitous component of traffic and industrial combustion emissions. The Aethalometer™ is used in urban locations to monitor high concentrations of combustion particles that may threaten public health. Its sampling port may be preceded by a size-selective inlet (e.g., cyclone, impactor) to measure particles in a specified aerodynamic size fraction.

The Aethalometer™ is especially well suited for measuring light absorption from burning diesel, oil, and coal. It was used in the Gulf War to monitor the effects of various smokes on health, visibility, and weapon systems. Aethalometers™ have also been installed at remote sites, including the Arctic, remote islands, wind-swept ocean coasts, the periphery of the Antarctic, and the South Pole, to measure the presence of black carbon in the atmosphere as an indicator of the long-range distribution of combustion-derived pollution. Aethalometers™ are in operation at the South Pole, in the deserts of Iraq and Iran, and across Europe and have been flown to the North Pole and all places in between.

Alternative Applications: Coupling an Aethalometer™, which measures optical absorption, with a nephelometer, which measures opti-

cal scattering, allows studies of the optical properties of aerosol-impacted ambient atmospheres and measures of the total light extinction in the atmosphere.

The Aethalometer™ can also be fitted with a special inlet to measure the amount of black carbon incorporated in fog or cloud droplets. In this way, the interaction between pollution and clouds or fogs can be studied in real time.

Existing/Near Term (2–4 years)/Far Term (≥5 years): The Aethalometer™ was developed in the late 1970s and manufactured in the late 1980s. More than a hundred instruments have been distributed, primarily to research laboratories and research stations at remote locations.

Mechanism of Action: The Aethalometer™ was developed as a real-time analyzer for measuring black carbon concentrations in the atmosphere, which can be related to the light-absorption coefficient. The Aethalometer™ measures the attenuation of a light beam transmitted through a quartz fiber filter on which black carbon is collected as a sample is drawn through. The system automatically advances the quartz fiber tape to a new position after a specified attenuation or time period is reached. The rate of accumulation of black carbon is proportional to both the black carbon concentration in the air stream and to the flow rate. A separate portion of the filter tape outside of the sample stream is used as an optical reference. The two parts of the filter, exposed and referenced, are illuminated by a stabilized lamp that provides diffused lighting. The light passing through the exposed and referenced portions of the filter is captured by two matched photodiodes, compared, and converted to optical attenuation values that are proportional to the quantity of light-absorbing particles collected on the filter.

Platform: The Aethalometer™ is an ambient monitor for carbonaceous particles that has been installed from inner cities to the most remote stations, onboard aircraft to measure vertical profiles of black carbon concentration, onboard ships to map the distribution of black carbon over the oceans, and in automobiles to study the exposure of vehicle passengers to traffic-related emissions.

Chemicals/Pollutants Detected: The Aethalometer™ detects aerosol black carbon from sources including motor vehicle exhaust, residential wood combustion, paved road dust and entrained geolog-

ical material, coal-fired boilers at power plants, and restaurant grills and residential cooking.

Accuracy/Reliability/Thresholds: The Aethalometer™ can detect an increment of 1 nanogram of black carbon on its filter. The ambient concentration to which this corresponds depends on the air flow rate and the integration time. Typical urban black carbon concentrations range from 1,000 to 50,000 ng/m3. If the black carbon concentration is very low, the flow rate and the integration time must be increased.

Data Collection, Availability, and Processing Requirements: The data are processed through an algorithm and provided as units of aerosol light absorption per cubic meter of air sampled. The instrument is self-calibrating. The Aethalometer™ requires no collection and analysis of samples and no data tracking. Since the Aethalometer™ does not measure mass, it must be calibrated againt the EPA's FRM.

Advantages: The Aethalometer™ is automatic and requires no operator intervention for normal operation. The instrument is user friendly, is fully operable upon unpacking, and is self-calibrating. Each roll of filter tape material can last from months to years, depending on the black carbon concentration at the sampling location.

The Aethalometer™ is not affected by temperature or relative humidity, and its sampled air stream does not need to be preconditioned. In addition, it is not affected by interference from other common aerosol species, such as natural aerosols (e.g., sea salt), or secondary anthropogenic aerosols (e.g., organics, sulfates, or nitrates).

Disadvantages: The Aethalometer™ does not make direct measurements of PM mass, but instead responds to the optically absorbing carbonaceous component of suspended particles from which the mass must be inferred. Therefore, the Aethalometer™ must be calibrated against the EPA's FRM. In addition, the Aethalometer™ only measures PM containing a carbonaceous component and cannot measure total PM, which can be made up of several different chemical species, including organics, sulfates, and nitrates.

Cost: The cost of a basic Aethalometer™ is $9,950 and, with all the options possible, is less than $13,000.

CONTINUOUS PARTICULATE MONITOR (CPM) [14, 15]

Applications: CPMs are variants of opacity meters used for stack sampling of PM emissions, and to monitor filter-bag bleedthrough, leaks, and broken-bag failures.

Existing/Near Term (2–4 years)/Far Term (≥5 years): CPMs are commercially available for monitoring of PM emissions.

Mechanism of Action: The CPM is an optically based unit that uses a microprocessor, transmitter, and receiver. It is a cross-stack measurement requiring two points of access. When light passes between the transmitter and receiver, the momentary absorption of light by the particles causes the receiver to see a modulating signal from the transmitter. This signal modulation increases with and relates to increasing dust concentrations. The signal can be calibrated with a known dust sample or used as a relative monitoring signal. The receiver senses the signal modulation and converts it to a dust concentration with the microprocessor.

Platform: CPMs are used for stack sampling and to monitor filter-bag bleedthrough, leaks, and breaks.

Chemicals/Pollutants Detected: CPMs are used to monitor PM, such as dust, dirt, soot, smoke, and aerosols (liquid droplets).

Accuracy/Reliability/Thresholds: The upper detection limit on particle loading of the CPM is about 4 gr/dscf and the lower detection limit is about $4x10^{-6}$ gr/dscf. The particle size range over which the instrument can effectively make measurements is 0.3 to 150 μm.

Data Collection, Availability, and Processing Requirements: CPMs do not measure mass and must be calibrated against the FRM.

Advantages: CPMs can be used for continuous, *in situ* monitoring and have excellent sensitivity. CPM systems are easy to install and set up, and all adjustments can be made by the operator.

Since CPMs measure signal modulation resulting from moving particles rather than diminishing intensity (brightness) of a light beam, the instrument is unaffected by conditions that cause false readings in an opacity system, such as dirty sensors, misaligned sensors, aging sources, or aging detectors. The CPM will continue to operate with-

out drift until 93 percent of the transmitted light is blocked. This is normally only 2 percent for typical opacity systems. Also, since it utilizes a diverging light source, it does not rely on lenses and instead uses a small window to separate the sensor electronics from the gas stream. Windows are unaffected by accumulation of dust and also unaffected by misalignment of the sensors. Because of this type of operation, CPMs can monitor even when moisture is present.

Disadvantages: CPMs are sensitive to particle size distribution and particle characteristics. In addition, CPMs do not measure mass and therefore must be calibrated against the EPA's FRM.

Cost: CPMs are commercially available for approximately $15,000.

THREE-COLOR INTEGRATING NEPHELOMETER WITH SIZE-SELECTIVE INLET [12, 18]

Applications: Integrating nephelometers measure the visual quality of local ambient air by measuring the scattering of light due to particles in continuous air samples. Nephelometers can be used in areas containing local sources of pollution, areas where atmospheric conditions trap air pollutants, and general air quality monitoring networks.

Existing/Near Term (2–4 years)/Far Term (≥5 years): The three-color integrating nephelometer is an existing technology that is commercially available.

Mechanism of Action: The three-color integrating nephelometer measures scattering of light due to particles in the air sample. The nephelometer has an enclosed design and is vacuum tight. This permits drawing sample air through a particle-size-fractionating inlet with a 2.5 μm cutpoint, so the instrument responds only to light scattering by fine particles. This cutpoint excludes cloud or fog droplets, drizzle, and other coarse particles from the sample flow.

The three-color integrating nephelometer makes measurements at three colors and thereby provides information on the size distribution of the fine-particle aerosol. For example, it is possible to reliably distinguish between times when the aerosol is dominated by photochemically formed particles, which have a geometric mean diameter (Dgv) in the 0.1 to 0.3 μm range, and droplet mode particles, which have a Dgv in the 0.5 to 0.7 μm range. The instrument collects data continuously. The sample chamber of the three-color nephelometer is illuminated by a tungsten lamp, and dichroic filters separate the scattered light into three wavelength ranges with nominal values of 450, 550, and 700 nm. The scattered light is detected by photomultipliers and photon-counting electronics.

Platform: Integrating nephelometers are used for ambient air monitoring.

Chemicals/Pollutants Detected: Nephelometers measure the visual quality of local ambient air by detecting PM, such as dust, dirt, soot, smoke, and aerosols (liquid droplets) from sources including motor vehicle exhaust, residential wood combustion, paved road dust and

entrained geological material, coal-fired boilers at power plants, and restaurant grills and residential cooking.

Accuracy/Reliability/Thresholds: The integrating nephelometer has a local visual distance ranging from 0.4 to 16.0 km and an accuracy of ±10 percent of the reading.

Data Collection, Availability, and Processing Requirements: The data files contain six light-scattering values in engineering units. These values are total scattering and backscattering at the red, green, and blue wavelengths. The three-color nephelometer is calibrated by filling it with Freon calibration gas. Since nephelometers do not measure mass, they must be calibrated against the EPA's FRM.

Advantages: The integrating nephelometer is simple to install, operate, and calibrate. It is sensitive and self-calibrating. Precise and accurate measurements can be made with few requirements for operator maintenance. It offers continuous sampling, has low power consumption and a rugged compact design, and is small and lightweight enough for field use. The solid-state electronics of the instrument are very stable. The instrument has proven to be an accurate, precise, and reliable means of monitoring ambient light scattering and has been applied in a wide range of operational and research monitoring programs in rural and urban areas.

Disadvantages: Integrating nephelometers are sensitive to particle size distribution and particle characteristics. In addition, integrating nephelometers do not measure mass and therefore must be calibrated against the EPA's FRM.

Cost: Integrating nephelometers are commercially available for approximately $8,000 to $9,000.

LIGHT DETECTION AND RANGING (LIDAR) [19–23]

Applications: Lidar is used for remote detection of the presence, velocity and chemical makeup of "particles" ranging from aircraft and missiles to smoke, dust, and "invisible" gases. Differential Absorption Lidar (DIAL) has been used to measure ozone concentrations in the troposphere, aerosol distributions, air pollutant plumes, and air mass dispersion. Lidar has been used for military, commercial, and space applications.

Alternative Applications: Lidar can also be used to conduct oceanographic and meteorological research.

Existing/Near Term (2–4 years)/Far Term (≥5 years): Many investigations of persistent elevated pollution episodes, ozone, and aerosols have been conducted with lidar since the early 1970s.

Mechanism of Action: Lidar uses the same principle as radar. The lidar instrument transmits light out to a target. The transmitted light interacts with and is changed by the target. Some of this light is reflected (scattered) back to the instrument, where it is analyzed. The change in the properties of the light enables some property of the target to be determined. The time for the light to travel out to the target and back to the lidar is used to determine the range to the target. DIAL is used to measure chemical concentrations (such as ozone, water vapor, clouds, aerosols, and pollutants) in the atmosphere. A DIAL uses two different laser wavelengths, which are selected so that one of the wavelengths is absorbed by the molecule of interest, and the other wavelength is not. The difference in intensity of the two return signals can be used to deduce the concentration of the molecule being investigated.

Platform: Lidar is a remote-sensing technology that can be ground based, or deployed on aircraft, satellites, and the space shuttle.

Chemicals/Pollutants Detected: DIAL can be used to detect ozone; water vapor; aerosols; pollutants, such as ethylene, benzene, ammonia, and hydrocarbons; and clouds.

Accuracy/Reliability/Thresholds: The accuracy of lidar is typically less than 10 ppb. Resolution varies depending on what is being

observed. For example, a 90-meter resolution can be obtained for ozone, while a 15-meter resolution is obtained for aerosol.

Advantages: Lidar is extremely sensitive, has a large dynamic range, and can detect down to parts per billion.

Disadvantages: Issues of archiving and data processing arise because of the large amounts of data generated by lidar.

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