

# LESSON 3

## ***Fundamentals of Particulate Monitoring Network Design***

### **Goal**

To familiarize you with the general considerations and principles of PM and PM network design.

### **Objectives**

After completion of this lesson you should be able to:

1. define  $PM_{2.5}$  and  $PM_{10}$ .
2. differentiate among different modes of ambient aerosol size distributions, their chemical compositions, and relationships to  $PM_{2.5}$  and  $PM_{10}$ .
3. quantify the zones of influence and residence times for different particle size fractions.
4. define sources, residence times, and zones of influence for both, primary and secondary particle emissions.
5. describe the four types of  $PM_{2.5}$  monitoring networks.
6. describe the six types of specific sampling sites which are a part of  $PM_{2.5}$  network.
7. State the specific objectives of network design for particulate sampling.

### **Reading Assignment Topics**

- History of network design
- Uses of ambient  $PM_{2.5}$  and  $PM_{10}$  data
- Particle Properties
- Basic concepts of network design
- Network design objectives

## Procedure

1. Read sections 2.0 through 2.2.5 (pages 2-1 through 2-16) and 2.3.2 through 2.4.1 (pages 2-18 through 2-24) of *Guidance for the Network Design and Optimum Site Exposure for PM<sub>2.5</sub> and PM<sub>10</sub>*.
2. Complete the review exercise.
3. Check your answers using the answer key in Appendix A.
4. Review the pages from any material you missed.
5. Take Quiz 1 in the back of this manual. Check your answers using the Quiz 1 answer sheet in Appendix B. Review the pages in the reading material for any questions you may have missed.
6. Continue to Lesson 4

## Review Exercise

What is the range of aerodynamic diameters for particles in each on the following fraction ranges:

**Aerodynamic diameter size fraction range**

1. Nucleation: \_\_\_\_\_
2. Accumulation: \_\_\_\_\_
3. Coarse: \_\_\_\_\_
  
4. The resident lifetime of particles in the nucleation range is limited because they
  - a. serve as nuclei for cloud or fog droplets.
  - b. flocculate with other particles.
  - c. coagulate with larger particles.
  - d. choices a. and c.
  - e. choices b. and c.

Match each of the following network descriptions with the monitoring network type. Some answers maybe used once, more than once, or not at all.

- |        |  |            |
|--------|--|------------|
| 5. ___ | Track trends in ozone precursor emissions.   | a. SLAMS   |
| 6. ___ | Provide long-term measurements of $PM_{2.5}$ and other visibility-related observables in National Parks and Wildernesses throughout the U.S. | b. NAMS    |
| 7. ___ | Focus on community exposure surveillance.  | c. PAMS    |
| 8. ___ | Determine impact of significant sources on ambient pollution levels.   | d. IMPROVE |

9. What are the six objectives of the SLAMS PM<sub>2.5</sub> monitoring network?

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- 
- 

10. Particles with an aerodynamic diameter greater than 2.5  $\mu\text{m}$  are called \_\_\_\_\_ particles.

- a. ultrafine
- b. fine
- c. coarse
- d. granular

11. Aerodynamic diameters for PM<sub>10</sub> size fraction range from

- a. 0 to 2.5  $\mu\text{m}$ .
- b. 0 to 10  $\mu\text{m}$ .
- c. 2.5 to 10  $\mu\text{m}$ .
- d. 10 to 40  $\mu\text{m}$ .

12. Aerodynamic diameters for PM<sub>2.5</sub> size fraction range from

- a. 0 to 2.5  $\mu\text{m}$ .
- b. 0.5 to 2.5  $\mu\text{m}$ .
- c. 2.5 to 10  $\mu\text{m}$ .
- d. 2.5  $\mu\text{m}$  and greater.

Match the site description in Column A with the site name on Column B.

- |         |  |                             |
|---------|--|-----------------------------|
| 13. ___ | Intended to represent regional-scale $PM_{2.5}$ concentrations that may be a combination of contributions from several MPAs and non-urban source areas.              | a. Core Monitoring Sites    |
| 14. ___ | Used to provide long term monitoring for assessing trends and for performing future epidemiological studies.   | b. Daily Compliance Sites   |
| 15. ___ | Used to determine NAAQS compliance for 24-hour standards.  | c. Special Purpose Monitors |
| 16. ___ | May be located in industrial, residential, commercial, recreational, and other areas where a substantial number of people may spend a significant part of their day. | d. Transport Sites          |
| 17. ___ | Used to assess the effects of emissions within one MPA on other MPAs   | e. NAMS Sites               |
| 18. ___ | Can be used to define community air quality for purposes of making comparisons to annual $PM_{2.5}$ NAAQS.   | f. Background Sites         |

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## **Required Readings**

## 2.0 CONCEPTS OF NETWORK DESIGN

Several new concepts and definitions are embodied in the form of the revised air quality standards. A brief overview of these concepts and definitions is given in this section.

### 2.1 Particle Properties

A wide variety of suspended particles are found in a typical atmosphere. Size, chemical composition, concentration, and temporal variability all have the potential to affect public health and perception of pollution. Several of these same properties allow suspended particles to be attributed to their sources.

Friedlander (1970, 1971) proposes a size-composition probability density function (PDF) to describe the number of suspended particles at given times and points in space with specified chemical composition and particle size. While a useful theoretical concept, the exact PDF can never be obtained in practice with current technology. Since all sizes and every chemical component of particles cannot be measured everywhere at all times, the measurement problem must be narrowed in scope to identify those properties that are important for compliance.

Figure 2.1.1 shows the major features of the mass distribution of particle sizes found in the atmosphere. The "nucleation" range, also termed "ultrafine particles", consists of particles with diameters less than  $\sim 0.08 \mu\text{m}$  that are emitted directly from combustion sources or that condense from cooled gases soon after emission. The lifetimes of particles in the nucleation range are usually less than one hour because they rapidly coagulate with larger particles or serve as nuclei for cloud or fog droplets. This size range is detected only when fresh emissions sources are close to a measurement site or when new particles have been recently formed in the atmosphere.

The "accumulation" range consists of particles with diameters between  $0.08$  and  $\sim 2 \mu\text{m}$ . These particles result from the coagulation of smaller particles emitted from combustion sources, from condensation of volatile species, from gas-to-particle conversion, and from finely ground dust particles. The nucleation and accumulation ranges constitute the "fine particle size fraction", and the majority of sulfuric acid, ammonium bisulfate, ammonium sulfate, ammonium nitrate, organic carbon and elemental carbon is found in this size range. Particles larger than  $\sim 2$  or  $3 \mu\text{m}$  are called "coarse particles"; they result from grinding activities and are dominated by material of geological origin. Pollen and spores also inhabit the coarse particle size range, as do ground up trash, leaves, and tires. Coarse particles at the low end of the size range also occur when cloud and fog droplets form in a polluted environment, then dry out after having scavenged other particles and gases.



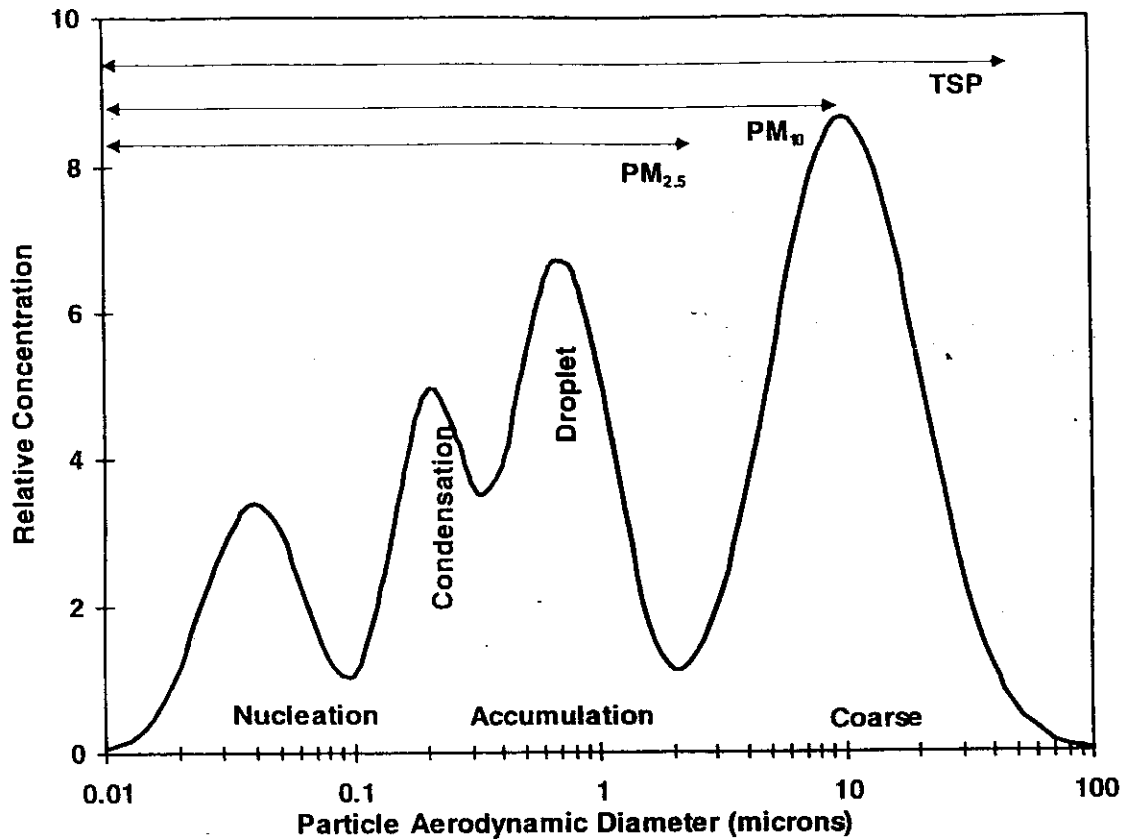


Figure 2.1.1. Idealized size distribution of particles in ambient air (Chow *et al.*, 1995).

Particle size fractions commonly measured by air quality monitors are identified in Figure 2.1.1 by the portion of the size spectrum that they occupy. The mass collected is proportional to the area under the distribution within each size range. The Total Suspended Particulate (TSP) size fraction ranges from 0 to ~40  $\mu\text{m}$ , the  $\text{PM}_{10}$  fraction ranges from 0 to 10  $\mu\text{m}$ , and the  $\text{PM}_{2.5}$  size fraction ranges from 0 to 2.5  $\mu\text{m}$  in aerodynamic diameter. No sampling device operates as a step function, passing 100% of all particles below a certain size and excluding 100% of the particles larger than that size. When sampled, each of these size ranges contains a certain abundance of particles above the upper size designation of each range.

Figure 2.1.2 shows typical residence times in the atmosphere for particle sizes within each size range, based on gravitational settling in mixed and stirred chambers (Hinds, 1982). Particles in the fine particle ( $\text{PM}_{2.5}$ ) size fraction have substantially longer residence times, and therefore the potential to affect PM concentrations further distant from emissions sources, than particles with aerodynamic diameters exceeding 2 or 3  $\mu\text{m}$ . In this regard, fine particles act more like gases than like coarse particles.

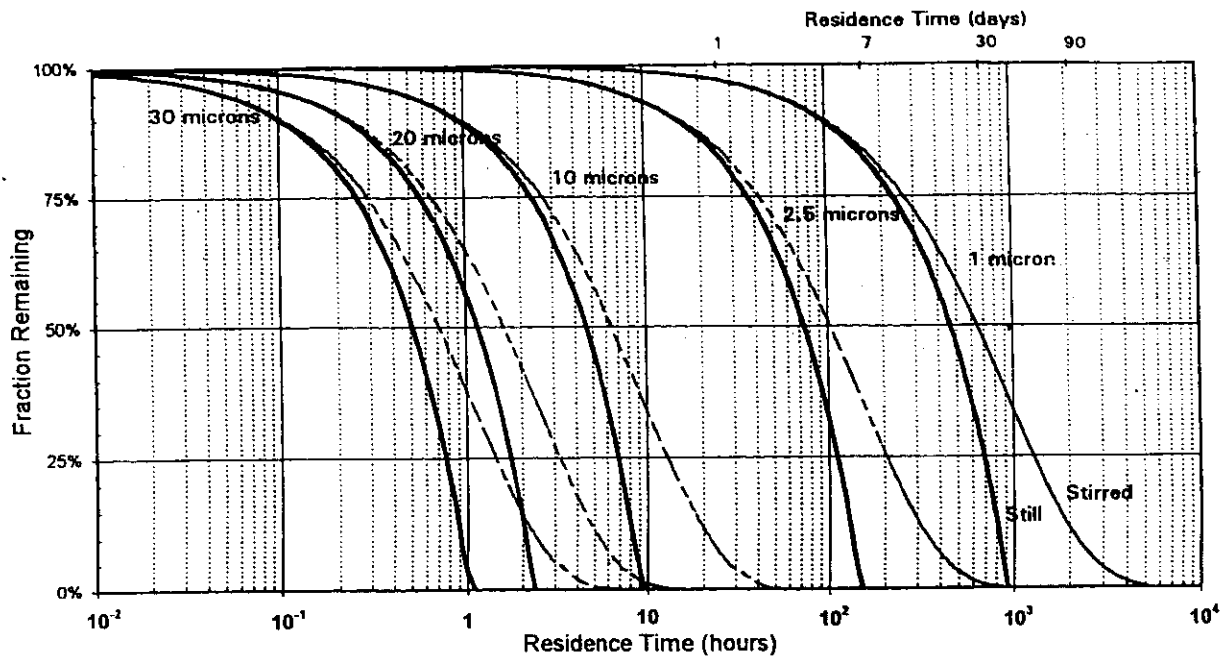


Figure 2.1.2. Residence times for homogeneously distributed particles of different aerodynamic diameters in a 100 m deep mixed layer. Gravitational settling is assumed for both still and stirred chamber models (Hinds, 1982).

Figure 2.1.1 shows the accumulation range to consist of at least two sub-modes, which is contrary to many other presentations that show only a single peak in this region. Recent measurements of chemically specific size distributions show these sub-modes in several different urban areas. John *et al.* (1990) interpreted the peak centered at  $\sim 0.2 \mu\text{m}$  as a “condensation” mode containing gas-phase reaction products. John *et al.* (1990) interpreted the  $\sim 0.7 \mu\text{m}$  peak as a “droplet” mode resulting from growth by nucleation of particles in the smaller size ranges and by reactions that take place in water droplets. The liquid water content of ammonium nitrate, ammonium sulfate, sodium chloride, and other soluble species increases with relative humidity, and this is especially important when relative humidity exceeds 70%. When these modes contain soluble particles, their peaks shift toward larger diameters as humidity increases.

The peak of the coarse mode may shift between  $\sim 6$  and  $25 \mu\text{m}$ . A small shift in the 50% cut-point of a  $\text{PM}_{10}$  sampler has a large influence on the mass collected because the coarse mode usually peaks near  $10 \mu\text{m}$ . On the other hand, a similar shift in cut-point near  $2.5 \mu\text{m}$  has a small effect on the mass collected owing to the low quantities of particles in the 1 to  $3 \mu\text{m}$  size range.

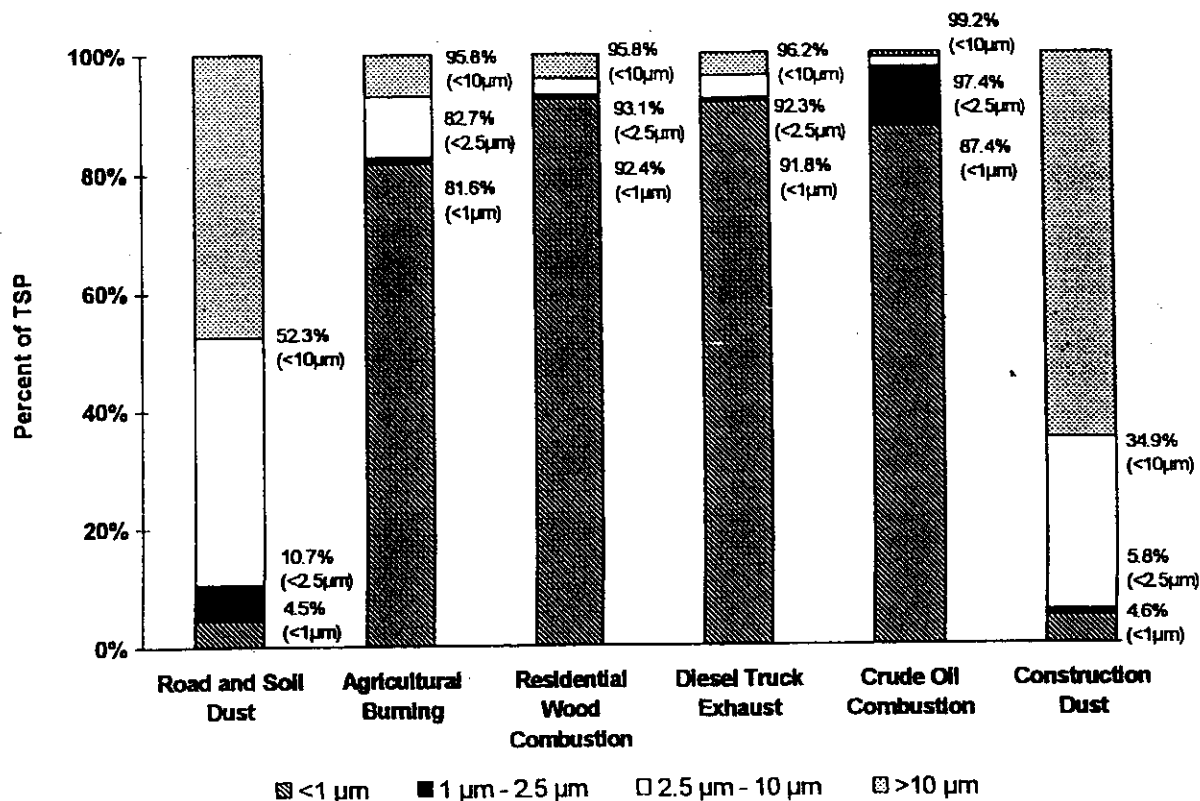


Figure 2.1.3. Size distributions of several particulate source emissions (Ahuja *et al.* 1989; Houck *et al.*, 1989, 1990).

Six major components account for nearly all of the  $PM_{10}$  mass in most urban areas: 1) geological material (oxides of aluminum, silicon, calcium, titanium, and iron); 2) organic carbon (consisting of hundreds of compounds); 3) elemental carbon; 4) sulfate; 5) nitrate; and 6) ammonium. Liquid water absorbed by soluble species is also a major component when the relative humidity exceeds  $\sim 70\%$ , but much of this evaporates when filters are equilibrated prior to weighing. Water-soluble sodium and chloride are often found in coastal areas, and certain trace elements are found in areas highly influenced by industrial sources.

Although total mass measurements are somewhat dependent on the sampling and analysis methods (Chow, 1995), with reasonable assumptions regarding the chemical form of mineral oxides and organic species, the mass concentrations of  $PM_{10}$  and  $PM_{2.5}$  can be reproduced within experimental precision (typically  $< \pm 10\%$ ) by summing the measured concentrations of these six chemical components. Comparison of the "reconstructed mass" from this method to measured total mass, when possible, is recommended as a data validation technique. Approximately half of  $PM_{10}$  is often composed of geological material. Geological material often constitutes less than  $\sim 10\%$  of the  $PM_{2.5}$  mass concentrations, however, as most of it is found in the coarse particle size fraction. As shown in Figure 2.1.3 (from Ahuja *et al.*, 1989; Houck *et al.*, 1989, 1990), most particles emitted by common sources, with the exception of fugitive dust sources, are in the  $PM_{2.5}$  fraction.

Source Type	Dominant Particle size	Chemical Abundances in Percent Mass			
		< 0.1%	0.1 to 1 %	1 to 10 %	> 10 %
Paved Road Dust	Coarse	Cr, Sr, Pb, Zr	SO <sub>4</sub> <sup>2-</sup> , Na <sup>+</sup> , K <sup>+</sup> , P, S, Cl, Mn, Zn, Ba, Ti	Elemental Carbon (EC), Al, K, Ca, Fe	Organic Carbon(OC), Si
Unpaved Road Dust	Coarse	NO <sub>3</sub> <sup>-</sup> , NH <sub>4</sub> <sup>+</sup> , P, Zn, Sr, Ba	SO <sub>4</sub> <sup>2-</sup> , Na <sup>+</sup> , K <sup>+</sup> , P, S, Cl, Mn, Ba, Ti	OC, Al, K, Ca, Fe	Si
Construction	Coarse	Cr, Mn, Zn, Sr, Ba	SO <sub>4</sub> <sup>2-</sup> , K <sup>+</sup> , S, Ti	OC, Al, K, Ca, Fe	Si
Agricultural Soil	Coarse	NO <sub>3</sub> <sup>-</sup> , NH <sub>4</sub> <sup>+</sup> , Cr, Zn, Sr	SO <sub>4</sub> <sup>2-</sup> , Na <sup>+</sup> , K <sup>+</sup> , S, Cl, Mn, Ba, Ti	OC, Al, K, Ca, Fe	Si
Natural Soil	Coarse	Cr, Mn, Sr, Zn, Ba	Cl <sup>-</sup> , Na <sup>+</sup> , EC, P, S, Cl, Ti	OC, Al, Mg, K, Ca, Fe	Si
Lake Bed	Coarse	Mn, Sr, Ba	K <sup>+</sup> , Ti	SO <sub>4</sub> <sup>2-</sup> , Na <sup>+</sup> , OC, Al, S, Cl, K, Ca, Fe	Si
Motor Vehicle	Fine	Cr, Ni, Y	NH <sub>4</sub> <sup>+</sup> , Si, Cl, Al, Si, P, Ca, Mn, Fe, Zn, Br, Pb	Cl <sup>-</sup> , NO <sub>3</sub> <sup>-</sup> , SO <sub>4</sub> <sup>2-</sup> , NH <sub>4</sub> <sup>+</sup> , S	OC, EC
Vegetative Burning	Fine	Ca, Mn, Fe, Zn, Br, Rb, Pb	NO <sub>3</sub> <sup>-</sup> , SO <sub>4</sub> <sup>2-</sup> , NH <sub>4</sub> <sup>+</sup> , Na <sup>+</sup> , S	Cl <sup>-</sup> , K <sup>+</sup> , Cl, K	OC, EC
Residual Oil Combustion	Fine	K <sup>+</sup> , OC, Cl, Ti, Cr, Co, Ga, Se	NH <sub>4</sub> <sup>+</sup> , Na <sup>+</sup> , Zn, Fe, Si	V, OC, EC, Ni	S, SO <sub>4</sub> <sup>2-</sup>
Incinerator	Fine	V, Mn, Cu, Ag, Sn	K <sup>+</sup> , Al, Ti, Zn, Hg	NO <sub>3</sub> <sup>-</sup> , Na <sup>+</sup> , EC, Si, S, Ca, Fe, Br, La, Pb	SO <sub>4</sub> <sup>2-</sup> , NH <sub>4</sub> <sup>+</sup> , OC, Cl
Coal-Fired Boiler	Fine	Cl, Cr, Mn, Ga, As, Se, Br, Rb, Zr	NH <sub>4</sub> <sup>+</sup> , P, K, Ti, V, Ni, Zn, Sr, Ba, Pb	SO <sub>4</sub> <sup>2-</sup> , OC, EC, Al, S, Ca, Fe	Si
Oil-Fired Power Plant	Fine	V, Ni, Se, As, Br, Ba	Al, Si, P, K, Zn	NH <sub>4</sub> <sup>+</sup> , OC, EC, Na, Ca, Pb	S, SO <sub>4</sub> <sup>2-</sup>
Smelter Fine	Fine	V, Mn, Sb, Cr, Ti	Cd, Zn, Mg, Na, Ca, K, Se	Fe, Cu, As, Pb	S
Antimony Roaster	Fine	V, Cl, Ni, Mn	SO <sub>4</sub> <sup>2-</sup> , Sb, Pb	S	None reported
Marine	Fine and Coarse	Ti, V, Ni, Sr, Zr, Pd, Ag, Sn, Sb, Pb	Al, Si, K, Ca, Fe, Cu, Zn, Ba, La	NO <sub>3</sub> <sup>-</sup> , SO <sub>4</sub> <sup>2-</sup> , OC, EC	Cl <sup>-</sup> , Na <sup>+</sup> , Na, Cl

**Table 2.1.1. Chemicals from particles in different emissions sources**

The actual chemical components found in a given ambient sample have a strong correspondence to the chemical composition of the source emissions in the monitored airshed. Table 2.1.1 (from Chow, 1995) shows the relative abundance of several elements, inorganic compounds, and carbon from different source types. The most abundant species in air are also most abundant in source emissions, with the exception of sulfate, nitrate, and ammonium. Spatial gradients in the concentrations of one or more of these species dominated by a single source provide a good means of evaluating the zone of influence of that source.

Sulfate, nitrate, and ammonium abundances in directly emitted particles are not sufficient to account for the concentrations of these species measured in the atmosphere. Ambient mass concentrations contain both primary and secondary particles. Primary particles are directly emitted by sources and usually undergo few changes between source and receptor. Atmospheric concentrations of primary particles are, on average, proportional to the quantities that are emitted.

Secondary particles are those that form in the atmosphere from gases that are directly emitted by sources. Sulfur dioxide, ammonia, and oxides of nitrogen are the precursors for sulfuric acid, ammonium bisulfate, ammonium sulfate, and ammonium nitrate particles. "Heavy" volatile organic compounds (HVOC, those containing more than eight carbon atoms) may also change into particles; the majority of these transformations result from intense photochemical reactions that also create high ozone levels. Secondary particles usually form over several hours or days and attain aerodynamic diameters between 0.1 and 1  $\mu\text{m}$ , as shown in Figure 2.1.1. Several of these particles, notably those containing ammonium nitrate, are volatile and transfer mass between the gas and particle phase to maintain a chemical equilibrium. This volatility has implications for ambient concentration measurements as well as for gas and particle concentrations in the atmosphere.

Ambient concentrations of secondary aerosols are not necessarily proportional to quantities of emissions since the rate at which they form may be limited by factors other than the concentration of the precursor gases. Secondary particulate ammonium nitrate concentrations depend on gaseous ammonia and nitric acid concentrations as well as temperature and relative humidity. A nearby source of ammonia may cause a localized increase in  $\text{PM}_{2.5}$  concentrations by shifting the equilibrium from the gas to the particulate ammonium nitrate phase (Watson *et al.*, 1994). Ammonium sulfate may form rapidly from sulfur dioxide and ammonia gases in the presence of clouds and fogs, or slowly in dry air. Because fine particle deposition velocities are slower than those of the gaseous precursors,  $\text{PM}_{2.5}$  may travel much farther than the precursors, and secondary particles precursors are often found far from their emissions sources and may extend over scales exceeding 1,000 km.

Compliance measurements are taken at fixed monitoring sites for specified time intervals, usually 24 hours. While fixed site monitoring is an effective surrogate for actual exposure, the air that people breathe depends on where they are, the most common locations being the home, the workplace, the automobile, and the outdoors. Most outdoor human exposure occurs during the daytime, so it is important to understand how particle concentrations differ between day and night.

Figure 2.1.4 shows a clear diurnal cycle of hourly  $\text{PM}_{2.5}$  concentrations measured with a TEOM during the 26-day IMS95 Winter Study (Chow and Egami, 1997). This plot shows a distinct diurnal pattern for the 50<sup>th</sup> and 80<sup>th</sup> percentile concentrations which is consistent with emissions estimates and meteorological patterns during the winter in the southern San Joaquin Valley. Because much of the  $\text{PM}_{2.5}$  is directly or indirectly related to emissions from motor vehicle exhaust, peaks of  $\text{PM}_{2.5}$  concentrations during the morning and evening rush hours are expected at urban sites. The evening peak is suspected to be the accumulation of emissions from motor vehicle exhaust superimposed on domestic cooking and residential wood combustion contributions. Since transport and mixing are lowest during the cold evening hours, pollutant concentrations can build up rapidly after sunset and frequently carry over to the next morning.

Meyer *et al.* (1992) show a similar diurnal pattern during wintertime in a mountainous California community where wood is burned, with the evening peak remaining high well past

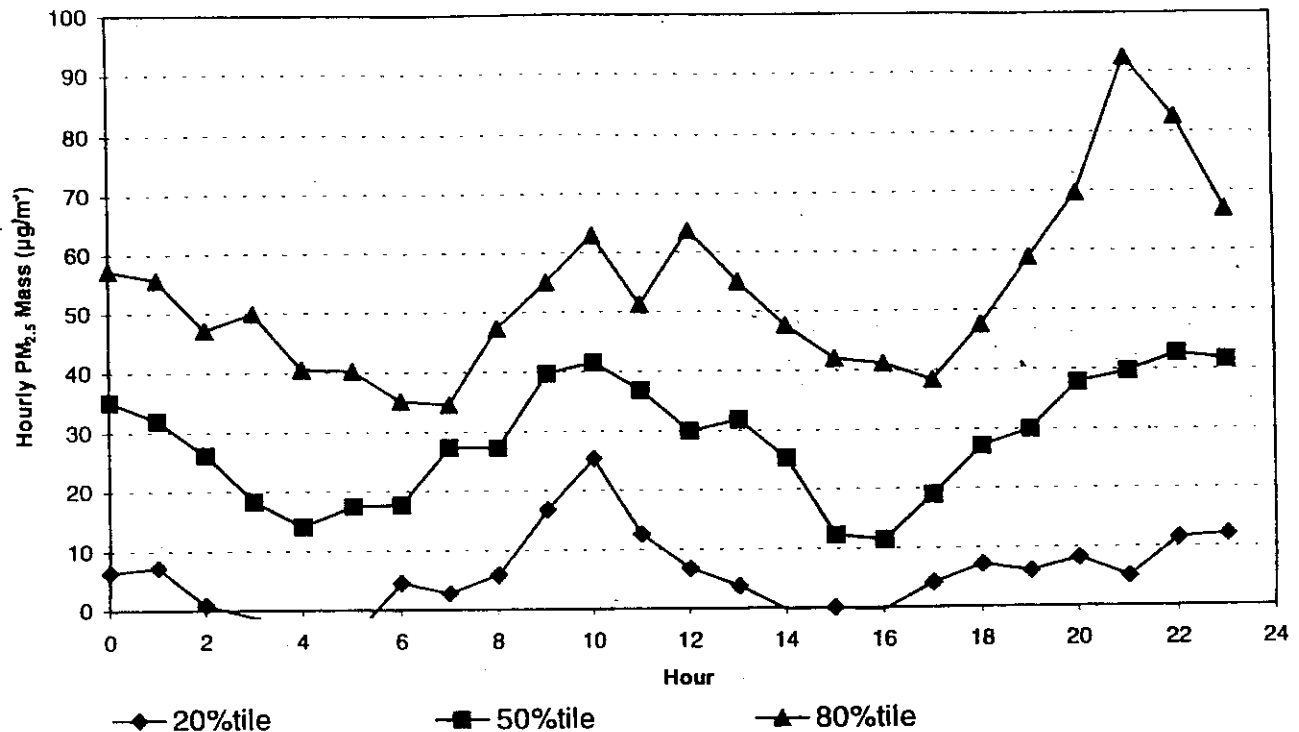


Figure 2.1.4. Hourly variations in the 20th, 50th, and 80th percentiles of PM<sub>2.5</sub> in Bakersfield, CA (Chow and Egami, 1997).

midnight. In some communities where fugitive dust is a major emitter, peak PM<sub>10</sub> concentrations may occur during the afternoon when ventilation is good, but high winds raise the dust into the air. The data in Figure 2.1.4 imply that a person's maximum outdoor exposure to suspended particles near the measurement site occurs during morning and evening commuting periods.

A PM sampler location, especially its proximity to local sources, can play a large role in its ability to assess spatial variability and source contributions. Figure 2.1.5 illustrates the spatial variability of PM<sub>10</sub> mass in a saturation monitoring network in California's San Joaquin Valley (Chow and Egami, 1997). During this study, most of the PM<sub>10</sub> mass was in the PM<sub>2.5</sub> fraction. All scales of representation show the highly variable nature of fine particulate mass averaged over 24 hours. The variations are most noticeable in the urban areas where the variability was attributable to residential wood smoke and holiday driving patterns. Figure 2.1.6 shows the difference in PM<sub>10</sub> chemical components in the same air basin. Sulfate, nitrate, and ammonium concentrations in these 24-hour samples are fairly uniform over each scale of representation. Organic carbon and crustal concentrations are more variable between measurement locations.

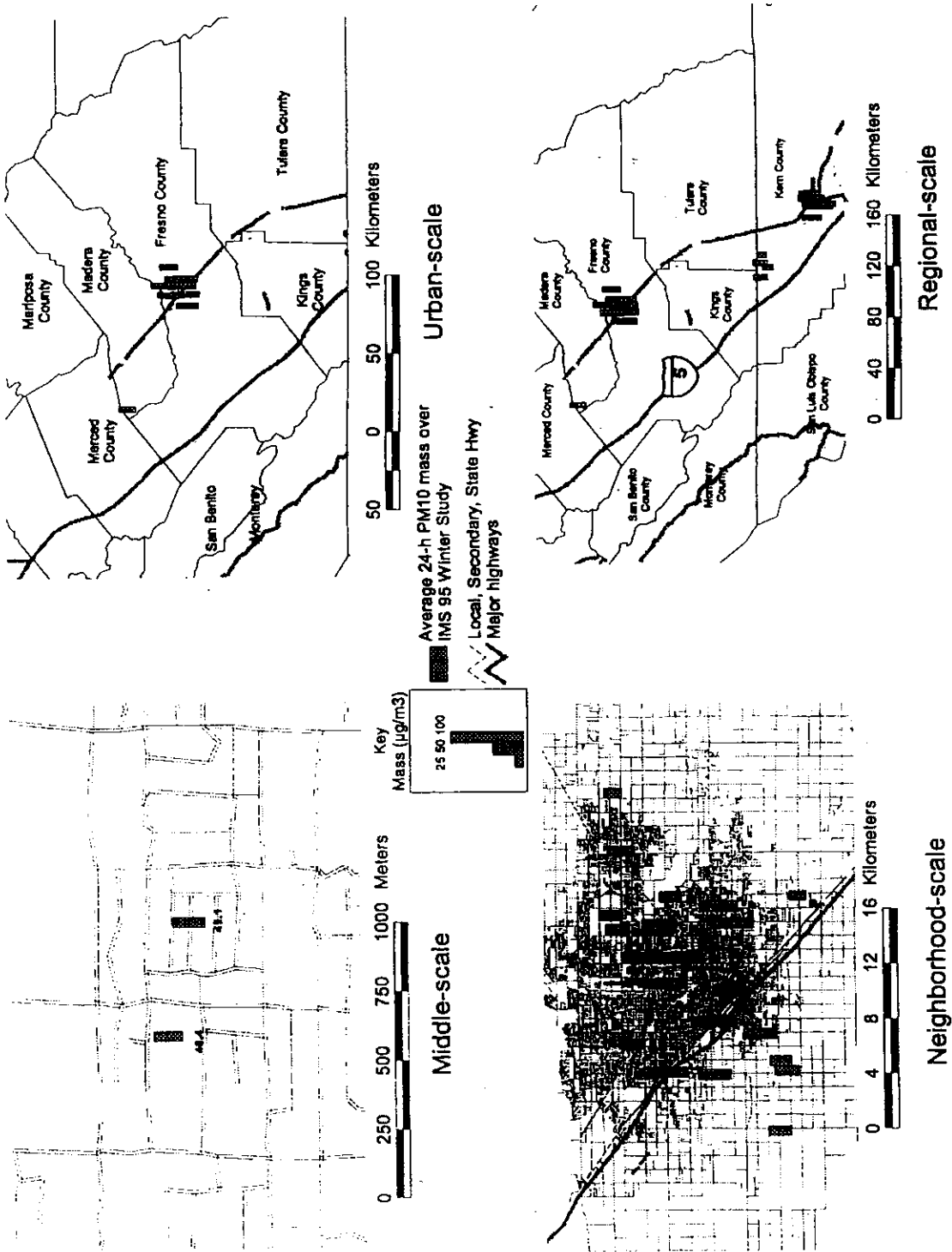
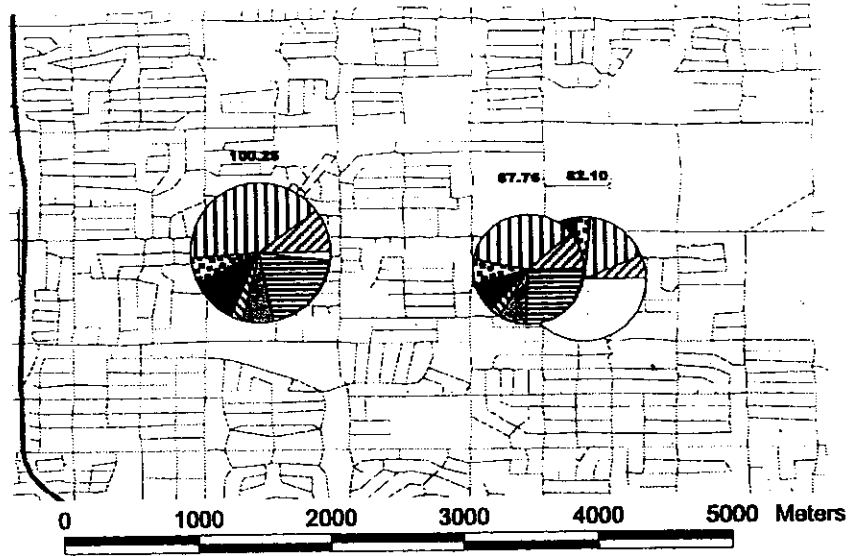
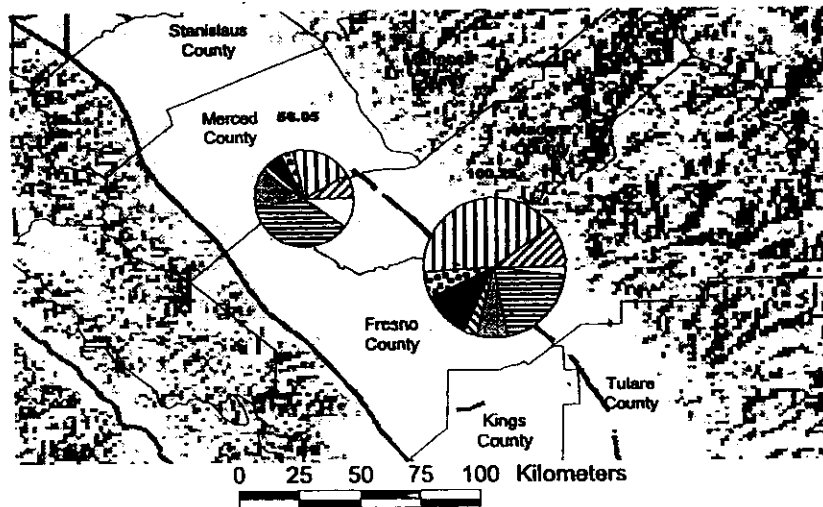


Figure 2.1.5.  $\text{PM}_{10}$  concentrations at different nearby sites centered around Fresno, CA.

a) Neighborhood Scale  
50m to 4 km



b) Urban Scale  
4 to 100 km



c) Regional Scale  
100 to 1000 km

- 12-27-95 24-h PM<sub>10</sub> Mass (µg/m<sup>3</sup>)
- Crustal
  - Organic Material
  - Trace Species
  - Elemental Carbon
  - Sulfate Ion
  - Ammonium Ion
  - Nitrate Ion
  - Unidentified
- Roads
- Local, Secondary, State Hwy
  - Interstate

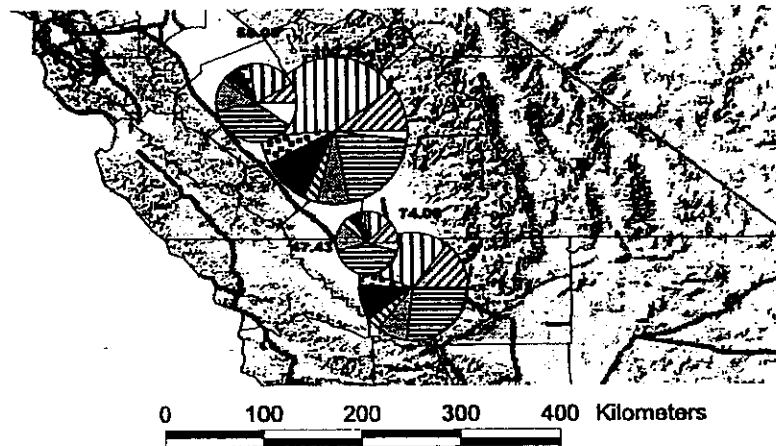
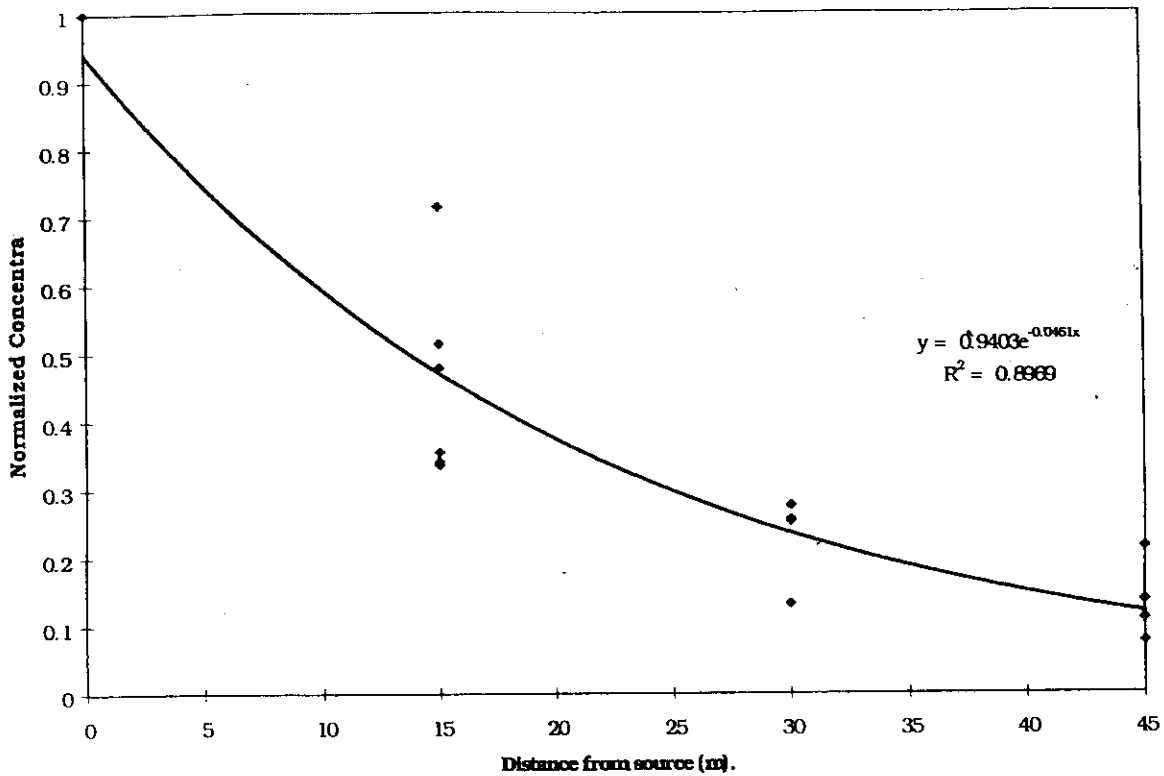


Figure 2.1.6. Spatial variation in 24-hour PM<sub>10</sub> chemical compositions from the neighborhood to regional scale.





**Figure 2.1.7.** Normalized  $PM_{10}$  concentrations at increasing distances from an unpaved road (Watson *et al.*, 1996). Samples were taken at 2 m above ground level.

$PM_{2.5}$  concentrations are often more homogeneously distributed over space than are the contributions from coarse-mode, geological sources. There are exceptions, however, as shown by Chow *et al.* (1989) in comparing high wood smoke contributions between a residential and an urban sampling site separated by less than 10 km. The stagnant air conditions prevailing during high wintertime episodes caused the wood smoke to contribute nearly 50% of  $PM_{10}$  at the residential site, but to contribute less than 10% of  $PM_{10}$  at the urban-commercial site. This is also evident in the variability of organic carbon in Figure 2.1.6.

These spatial variations occur because particles deposit and disperse rapidly with distance from an emissions source. Figure 2.1.7 shows how  $PM_{10}$  caused by dust emitted by an unpaved road decreases with downwind distance from the edge of the road. Figure 2.1.2 indicates that deposition over time intervals required to traverse these distances is low, so that much of the decrease in concentration is probably due to vertical mixing and dispersion.

Outdoor particle mass concentrations, corresponding indoor measurements, and measurements from personal exposure monitors carried by test subjects are often poorly correlated. The correspondence between these three types of samples is much better for some chemical species, such as sulfate. When indoor concentrations were apportioned to sources

in Riverside, CA (Pellizari *et al.*, 1993), particle loadings in outdoor air accounted for more than 60% of the indoor PM<sub>2.5</sub>. Particles from smoking, cooking, house dust, and other indoor emissions constituted the remainder of indoor concentrations.

The lack of correlation between indoor and outdoor measurements does not mean that outdoor concentrations are unimportant. While residents can control indoor emissions through personal actions such as using filtered vacuum cleaners and exhausting cooking emissions, there is little that they can do to prevent the incursion of pollution from outdoor air. Smaller particles, such as PM<sub>2.5</sub>, are more likely to penetrate indoors than are the coarse particles, which are more likely to deposit within the cracks and seams where air penetrates. Coarse particles also deposit to surfaces more rapidly due to gravitational settling in the stilled air of most indoor environments.

Most of the evidence relating ambient measurements of suspended particles taken in compliance networks to personal exposures shows that: 1) ambient concentrations, especially those for PM<sub>2.5</sub> particles, constitute a major fraction of the particles to which humans are exposed; and 2) ambient levels generally represent a lower bound on the concentrations to which people are commonly exposed.

## **2.2 Concepts**

Several new concepts are explicit or implicit in the new standards and their implementation. These relate to how particle concentrations vary over a monitored area, how measurements correspond to population levels, and how nearby and distant sources affect measurement locations.

### **2.2.1 Spatial Uniformity**

Spatial uniformity is the extent to which particle concentrations vary over a specified area. It is expressed as a spatial coefficient of variation of measured concentrations from many samplers in an area and as the deviation of measurements taken by a single sampler from the spatial average of all samplers. An annual coefficient of variation (standard deviation divided by the mean) of less than 10%, and a 20% maximum deviation of a single sampler from the mean, are desirable indicators of spatial uniformity for determining compliance with standards. This translates into an annual spatial standard deviation of no more than 1.5  $\mu\text{g}/\text{m}^3$ , and maximum deviations of no more than 3  $\mu\text{g}/\text{m}^3$ , at concentrations near the annual PM<sub>2.5</sub> standard of 15  $\mu\text{g}/\text{m}^3$ .

### **2.2.2 Receptor Site Zone of Representation**

PM<sub>10</sub> and PM<sub>2.5</sub> concentrations measured at any receptor result from contributions of emissions from nearby and distant sources and the zone of representation of a monitoring site depends on the relative amounts contributed by sources on different spatial scales. The dimensions given below are nominal rather than exact and are presented as defined in 40 CFR part 58. They indicate the diameter of a circle, or the length and width of a grid square, with a monitor at its center.

- **Collocated Scale (1 to 10 m):** Collocated monitors are intended to measure the same air and involve separations of 1 to 5 m between samplers. Collocated measurements should not differ by more than the operational precision of the monitoring method. Monitors are operated on collocated scales to evaluate the equivalence of different measurement methods and procedures and to quantify the measurement accuracy and precision of the same measurement methods and procedures. The distance between collocated samplers should be large enough to preclude the air sampled by any of the devices from being affected by any of the other devices, but small enough so that all devices obtain air containing the same pollutant concentrations.
- **Microscale (10 to 100 m):** Microscale monitors show significant differences between PM<sub>2.5</sub> monitors separated by 10 to 50 m. This often occurs when monitors are located right next to a low-level emissions source, such as a busy roadway, construction site, wood stove chimney, or short stack. Compliance monitoring site exposure criteria intend to avoid microscale influences even for source-oriented monitoring sites. A microscale zone of representation is primarily useful for studying emissions rates and zones of influence, as illustrated in Figure 2.1.7.
- **Middle Scale (100 to 500 m):** Middle-scale monitors show significant differences between locations that are ~0.1 to 0.5 km apart. These differences may occur near large industrial areas with many different operations or near large construction sites. Monitors with middle-scale zones of representation are often source-oriented, used to determine the contributions from emitting activities with multiple, individual sources to nearby community exposure monitors.
- **Neighborhood Scale (500 m to 4 km):** Neighborhood-scale monitors do not show significant differences in particulate concentrations with spacing of a few kilometers. This dimension is often the size of emissions and modeling grids used in large urban areas for PM source assessment, so this zone of representation of a monitor is the only one that should be used to evaluate such models. Sources affecting neighborhood-scale sites typically consist of small individual emitters, such as clean, paved, curbed roads, uncongested traffic flow without a significant fraction of heavy-duty vehicles, or neighborhood use of residential heating devices such as fireplaces and wood stoves.
- **Urban Scale (4 to 100 km):** Urban-scale monitors show consistency among measurements with monitor separations of 10's of km. These monitors represent a mixture of particles from many sources within the urban complex, including those from the smaller scales. PM measurements at urban-scale locations are not dominated by any particular neighborhood, however. Urban-scale sites are often located at higher elevations and away from highly traveled roads, industries, and residential heating. Monitors on the roofs of two- to four-story buildings, in the urban core area, are often good representatives of the urban scale.

- **Regional-Scale Background (100 to 1,000 km):** Regional-scale background monitors show consistency among measurements for monitor separations of a few hundred kilometers. Background concentrations are often more consistent for specific chemical compounds, such as sulfate or nitrate, than they are for PM mass concentrations. Regional-scale PM is a combination of naturally occurring aerosol from windblown dust and marine aerosol as well as particles generated in urban and industrial areas that may be more than 1,000 km distant. Regional-scale sites are best located in rural areas away from local sources, and at higher elevations. National parks, national wilderness areas, and many state and county parks and reserves are appropriate areas for regional-scale sites. Many of the IMPROVE sites characterize PM regional scale background in different regions of the U.S.
- **Continental-Scale Background (1,000 to 10,000 km):** Continental-scale background monitors show little variation even when they are separated by more than 1,000 km. They are hundreds of kilometers from the nearest significant emitters. Though these sites measure a mixture of natural and diluted manmade source contributions, the manmade component is at its minimum expected concentration. The Jarbidge Wilderness IMPROVE site in northern Nevada is a good example of a continental-scale background site for PM in North America.
- **Global-Scale Background(>10,000 km):** Global-scale background monitors are intended to quantify concentrations transported between different continents as well as naturally-emitted particles and precursors from sea spray, volcanoes, and windblown dust. Yellow sand from China has been detected at the Mauna Loa, HI, laboratory (Darzi and Winchester, 1982; Braaten and Cahill, 1986), and red dust from Africa's Sahara desert has been detected at Mt. Yunque, PR. Other global-scale sites include McMurdo, Palmer, and Ahmudson-Scott stations in Antarctica (Lowenthal *et al.*, 1996), Pt. Barrow, AK, and Mace Head, Ireland.

### 2.2.3 Community-Oriented Monitoring

Community-oriented (core) monitoring sites are beyond the zone of influence of a single source, and should have neighborhood- to urban- scale zones of representation. The principal purpose of community-oriented monitoring sites is to approximate the short-term and long-term exposures of large numbers of people where they live, work, and play. A monitor placed at the fence line of an emissions source would not be considered to represent community exposures, even though there might be residences abutting that fence line. A monitor placed in the middle of an area adjacent to a source would, however, be deemed a community exposure monitor for that neighborhood provided that the location represented a zone of at least 0.5 km in diameter. The fence line monitor might still be operated because it provides information on how much the nearby source contributes to the community-oriented site. The data from the fence line monitor would not be used to determine annual NAAQS compliance, though it might be used to make comparisons to the 24-hour standard or to design control strategies to bring the area into compliance with the annual NAAQS.

#### 2.2.4 Background and Regional Transport Monitoring

Background and regional transport (or boundary) monitors are located outside of local air quality jurisdictions to determine how much of the PM at community-oriented sites derives from external sources. Background sites are intended to quantify regionally representative PM<sub>2.5</sub> for sites located away from populated areas and other significant emission sources. Transport sites are intended to measure fine particle contributions from upwind source areas, or mixtures of source areas, that move into a planning area.

Most planning areas contain at least one substantial metropolitan area. Several of these also include industrial sources, either concentrated in one or a few districts or dispersed throughout the planning area. Air quality planning areas also contain less developed areas that may be distant from the densely populated centers and industrial emitters. These may include agricultural areas, dormant lands, large parks, wildlife and nature preserves, large military bases, etc.

Transport sites should be located upwind of planning area boundaries, outside of the urban-scale zone of influence. For the most part, transport sites are between planning areas, or between districts containing large emitters (e.g., industrial complexes, isolated point sources) and a planning area. Measurements from transport sites represent transport into the planning area only during periods when the wind is from the direction of the external source area toward the planning area. During other periods, the transport site may also serve the purposes of a background site, or as a transport site for another planning area. For this reason, transport site locations are selected to achieve multiple purposes. Meteorological data needed to evaluate which purposes are being served should be available along with the PM<sub>2.5</sub> measurements.

Background monitors are intended to measure PM<sub>2.5</sub> concentrations that are not dependent on upwind sources, although the particles they quantify will be a mixture of natural and manmade source material. These stations should be distant from identified emitters, and may be at higher elevations than the urban-scale community exposure monitors. Current IMPROVE (Interagency Monitoring of Protected Visual Environments) PM<sub>2.5</sub> monitoring in National Parks and Wilderness Areas (Eldred *et al.*, 1990) provides the best examples of background monitoring sites, but there is a dearth of these sites in the non-western states. Table 2.2.1 lists the locations of IMPROVE sites and their current measurements.

Properly sited background stations should measure PM<sub>2.5</sub> typical of the lowest ambient concentrations in a state or region. These sites should not be along transport pathways, though in densely populated or industrialized regions (such as the northeast corridor) a given sample may or may not be along such a pathway depending on which way the wind is blowing.

Several background sites may be needed in large and geographically diverse states, such as California and others in the west, where terrain produces major barriers to

Name	Latitude	Longitude	Elev (m)	AT	EX	SC	A	B	C	D	RH	SO2	35
Acadia NP	44.3742	68.2622	122	X		X	X	X	X	X	X	X	
Badlands NP	43.7469	101.9411	730				X	X	X	X			
	43.8719	102.2308	960	X	X						X		
Bandelier NM, Rim Fire Tower	35.7817	106.2675	1981	X	X		X	X	X	X	X		
Big Bend NP	29.3053	103.1772	1052				X	X	X	X		X	
	29.3439	103.2067	1082	X	X						X		
Boundary Waters Canoe Area	47.9467	91.4958	515	X		X	X	X	X	X	X		
Bryce Canyon NP	37.6000	112.1667	2530				X	X	X	X			
	37.4667	112.2278	2710										X
Bridger Wilderness	42.9750	109.7583	2627				X	X	X	X			
	42.9281	109.7875	2390	X	X						X		
Canyonlands NP	38.4583	109.8217	1814	X	X		X	X	X	X	X		
Cape Romain NWR	0.0000	0.0000	34				X	X	X	X			X
Chassahowitzka NWR	28.7500	82.5667	0				X	X	X	X		X	
Chiricahua NM	32.0097	109.3883	1570	X	X		X	X	X	X	X		
Crater Lake NP	42.8958	122.1333	1981				X	X	X	X			
Craters of the Moon NM	43.4606	113.5622	1815										X
Denali NP	63.7233	148.9675	661				X	X	X	X		X	
Death Valley NP	36.5086	116.8478	125				X			X		X	
Dome Land	35.7000	118.2000	950				X	X					
Dolly Sods Wilderness	39.1047	79.4258	1175				X	X	X	X			
E.D. Forsythe NWR	39.4681	74.4536	5				X	X	X	X			X
Everglades NP	25.3883	0.0000	2				X					X	
Glacier NP	48.5103	113.9956	975				X	X	X	X			
	48.5581	113.9375	968	X	X						X		
Great Basin NP	39.0053	114.2158	2060	X	X		X	X	X	X	X		
Grand Canyon NP	36.0392	111.8300	2290										X
(Hopi Point Fire Tower)	36.0719	112.1550	2164				X	X	X	X		X	
	35.9964	111.9917	2256	X	X						X		
	36.0778	112.1289	1158	X	X		X	X	X	X	X	X	
Great Sand Dunes NM	37.7083	105.5172	2487				X	X	X	X			
Great Smokey Mountains NP	35.6314	83.9422	793	X		X	X	X	X	X	X	X	
Guadalupe Mountains NP	0.0000	104.8097	1658	X	X		X	X	X	X	X		
Haleakala NP	20.8039	156.2850	1097				X						
Jarvis Wilderness	41.9583	115.0847	2400										X
	41.8925	115.4250	1889	X		X	X	X	X	X	X		
Lassen Volcanic NP	40.5369	121.5725	1756				X	X	X	X			
Lye Brook Wilderness	43.1444	73.1289	1010				X	X	X	X			
Mammoth Cave NP	37.2178	86.0736	219	X		X	X	X	X	X	X		X
Mesa Verde NP	37.1983	108.4903	2165				X	X	X	X			
Moosehorn NWR	0.0000	0.0000	40				X	X	X	X			
Mount Rainier NP	46.7614	122.1217	421	X		X	X	X	X	X	X		
National Capitol Central, D.C.	38.8950	77.0367	9				X	X	X	X			
Okefenokee NWR	30.7403	82.1286	38	X		X	X	X	X	X	X	X	
Petrified Forest NP	35.0772	109.7697	1755				X	X	X	X			
	34.8983	109.7958	1690	X	X						X		
Pinnacles NM	36.4850	121.1556	335				X	X	X	X			
Point Reyes NP	38.1231	122.9083	76				X	X	X	X			
Redwood National Seashore	41.5611	124.0828	235				X	X	X	X			
Rocky Mountain NP	40.2772	105.5450	2743				X	X	X	X			
	40.3606	105.5806	2536	X	X						X		
San Geronio Wilderness	34.1847	116.9019	1712	X	X		X	X	X	X	X		
Saguaro NM	32.1744	110.7364	938										X
Sequoia NP	36.4936	118.8286	521				X	X	X	X		X	
Shenandoah NP, Big Meadows	38.5219	78.4361	1073	X	X		X	X	X	X	X	X	
Sipsey Wilderness	34.3431	87.3386	311				X	X	X	X			
Tonto NM	33.6339	111.1011	792				X	X	X	X			
Upper Buffalo Wilderness	35.8269	93.2056	701	X	X		X	X	X	X	X		
Virgin Islands NP	18.3333	64.7942	46				X						
Voyageurs NP	48.5878	93.1728	343				X						X
Weminuche Wilderness Area	0.0000	0.0000	2758				X	X	X	X			
Yellowstone NP, Water Tank	44.5597	110.4000	2469				X	X	X	X		X	
Yosemite NP, Turtleneck Dome	37.7114	119.7044	1605	X	X		X	X	X	X	X		

KEY

AT ambient temperature (non-aspirated)	C IMPROVE sampler module C
EX extinction coefficient (transmissometer)	D IMPROVE sampler module D
SC scattering coefficient (nephelometer)	RH relative humidity sensor
A IMPROVE sampler module A	SO2 sulfur dioxide sampler
B IMPROVE sampler module B	35 35 mm camera slides

Table 2.2.1. IMPROVE measurement sites.

atmospheric flow. Regions lacking IMPROVE monitors should determine the proximity of National Parks, Wilderness Areas, and State Preserves as candidates for background sites. Background monitors also contribute to regional visibility goals that are part of other air quality regulations.

### 2.2.5 Emissions Zone of Influence

The zone of influence of a source is the distance at which PM from that specific source contributes no more than 10% of the measured PM concentration. The zone of influence refers to a specific emitter, rather than to a source category. For example, though suspended road dust may contribute 50% of PM<sub>10</sub> over a wide region, the majority of emissions from a specific road influence concentrations over a few tens of meters from the emissions point (see Figure 2.1.7).

The actual size of a zone of influence varies with meteorology, being larger downwind than upwind, and the nature of the source (point, elevated, area, line, etc.). Zones of influence are, therefore, expressed as orders of magnitude rather than as exact distances. The concept is useful for locating community exposure sites that are intended to represent concentrations for sources with large rather than small zones of influence. Actual zones of influence must be determined empirically, by spatially dense monitoring networks, or theoretically by applying air quality and meteorological models.

### 2.2.6 PM<sub>2.5</sub> Sampler Types

Measurement methods applied in PM networks are ground-based and are divided into three categories: Federal Reference Method (FRM) samplers, Federal Equivalent Method (FEM) samplers, and other samplers. The non-FRM samplers are distinguished by their level of similarity in design to Federal Reference Methods (FRM). The further from the FRMs in design, the more stringent are the requirements for designation of an instrument as an equivalent method.

- **Federal Reference Methods:** Federal Reference Methods for PM<sub>2.5</sub> are methods that have been designated as such under CFR 40 Chapter I Part 53, having met design and performance characteristics described in Part 50, Appendix L; Part 53, Subpart E; and Part 58, Appendix A. Reference method instruments acquire deposits over 24-hour periods on Teflon-membrane filters from air drawn at a controlled flow rate through a tested PM<sub>2.5</sub> inlet. The inlet and size separation components are specified by design, with drawings and manufacturing tolerances published in the Code of Federal Regulations. Most of the other measurement components and procedures are specified by performance characteristics, with specific test methods to assess that performance.
- **Class I Equivalent Methods:** Class I equivalent method instruments maintain the same measurement principles as reference method instruments, but with minor design changes. Class I instruments are intended to provide for sequential sampling without operator intervention at measurement sites that sample every

day. Testing of design and performance characteristics for Class I instruments is given in Part 53, Subpart E.

- **Class II Equivalent Methods:** Class II equivalent method instruments include all other instruments based on a 24-hour integrated filter sample with subsequent moisture equilibration and gravimetric mass analysis, but differ substantially in design from the reference method instruments. More extensive performance testing is required for a Class II equivalent instrument than for reference or Class I equivalent instruments. Testing of design and performance characteristics for Class II methods is given in Part 53, Subpart F.
- **Class III Equivalent Methods:** Class III equivalent method instruments include any candidate instruments that cannot qualify as Class I or Class II instruments. These may either be filter-based integrated samplers not meeting Class I or Class II criteria, or filter or non-filter based continuous or semi-continuous samplers. Test procedures and performance requirements for Class III candidate method instruments will be determined on a case-by-case basis. The testing for these instruments will be the most stringent, because equivalency to reference methods must be demonstrated over a wide range of particle size distributions and aerosol compositions. Other methods include all non-FRM or non-equivalent measurement methods capable of characterizing fine particles that may not be or have not yet been classified as an equivalent method. Existing manual and continuous analyzers are in this category and potentially include the dichotomous sampler, IMPROVE samplers, nephelometers, beta attenuation monitors, and Tapered Element Oscillating Microbalances (TEOMs). Such instruments are not precluded from becoming equivalent on a site-specific, regional or national basis.

## 2.3 Definitions

Several terms and abbreviations are used throughout this guidance, and in the specification of the method for determining compliance with the revised standards. These terms are defined for: 1) theoretical concepts; 2) monitoring boundaries; 3) monitoring networks; and 4) site types.

### 2.3.1 Theoretical Concepts

As will be shown in Section 2.4, systematic sampling theory has seldom been applied to the design of air quality measurement networks. Since monitoring resources are always finite, trade-offs must be made off between numbers of sites, frequencies of samples, sample durations, and the quantities measured. As more experience is gained in the design of PM<sub>2.5</sub> monitoring networks, the theoretical and empirical basis for network design will become better established.

- **Cost Per Error (CPE) (Borgman *et al.*, 1996):** Total cost of sample collection and analysis divided by estimated error. There is a balance between the cost savings with fewer sites against the costs of having larger errors.



- **Error Per Cost (EPC) (Borgman *et al.*, 1996):** This is the reciprocal of CPE. It quantifies the statistical uncertainty associated with a given amount of monitoring resources.

### 2.3.2 Monitoring Boundaries

The new standards refer to several boundaries. Metropolitan Statistical Areas, Primary Metropolitan Statistical Areas, Consolidated Metropolitan Statistical Areas, and New England County Metropolitan Areas are defined by the U.S. Office of Management and Budget, and these are defined in Appendix B for the 1990 census. Metropolitan Planning Areas and Community Monitoring Zones are areas with boundaries corresponding to subdivisions of the statistical areas that are to be defined by each state according to these guidelines.

- **Metropolitan Statistical Area (MSA):** MSAs are designated by the U.S. Office of Management and Budget (OMB) as having a large population nucleus, together with adjacent communities having a high degree of economic and social integration with that nucleus. MSA boundaries correspond to portions of counties, single counties or groups of counties that often include urban and non-urban areas. MSAs are useful for identifying which parts of a state have sufficient populations to justify the installation of a compliance monitoring network. Their geographical extents may be too big for defining the boundaries of Metropolitan Planning Areas and Community Monitoring Zones.
- **Primary Metropolitan Statistical Area (PMSA):** PMSAs are single counties or groups of counties that are the component metropolitan portions of a mega-metropolitan area. PMSAs are similar to MSAs with the additional characteristic of having a degree of integration with surrounding metropolitan areas. A group of PMSAs having significant interaction with each other are termed a Consolidated Metropolitan Statistical Area (CMSA).
- **Consolidated Metropolitan Statistical Area (CMSA):** A Consolidated Metropolitan Statistical Area (CMSA) is a group of metropolitan areas (PMSAs) that have significant economic and social integration.
- **New England County Metropolitan Statistical Area (NECMSA):** The OMB defines NECMAs as a county-based alternative for the city- and town-based New England MSAs and CMSAs. The NECMA defined for an MSA or CMSA includes:
  - The county containing the first-named city in that MSA/CMSA title (this county may include the first-named cities of other MSAs/CMSAs as well), and
  - Each additional county having at least half its population in the MSAs/CMSAs whose first-named cities are in the previously identified county. NECMAs are not identified for individual PMSAs. There are twelve

NECMAs, including one for the Boston-Worcester-Lawrence, MA-NH-ME-CT CMSA and one for the Connecticut portion of the New York-Northern New Jersey-Long Island, NY-NJ-CT-PA CMSA.

- **Monitoring Planning Area (MPA):** MPAs are defined by the state implementation plan as the basic planning unit for  $PM_{2.5}$  monitoring. A MPA is a contiguous geographic area with established, well-defined boundaries. MPAs may cross state lines and can be further subdivided into Community Monitoring Zones. A MPA does not necessarily correspond to the boundaries within which pollution control strategies will be applied. In fact, it is expected that emissions control regions will be much larger than the MPAs, owing to the superposition of regional-, urban-, and neighborhood-scale contributions to  $PM_{2.5}$ . MPAs may include aggregates of: 1) counties; 2) zip code regions; 3) census blocks and tracts; or 4) established air quality management districts. Counties are often much larger than the most densely populated areas they contain, and some large metropolitan areas may extend over several counties. Census blocks are very small and may be unwieldy to manipulate in some large areas. Zip code and census tract boundaries may be the most manageable units for many areas. These boundaries vary substantially in geography from one region to another. MPAs normally will contain at least 200,000 people, though portions of a state not associated with MSAs can be considered as a single MPA. Optional MPAs may be designated for other areas of a state. MPAs in MSAs are completely covered by one or more Community Monitoring Zones.
- **Community Monitoring Zone (CMZ):** When spatial averaging is utilized for making comparisons to the annual  $PM_{2.5}$  NAAQS, Community Monitoring Zones must be defined in the monitoring network description. Otherwise, they may be used as a more informal manner, as a means to describe the communities surrounding one or more core monitoring sites. CMZs have dimensions of 4 to 50 km with boundaries defined by existing political demarcations (e.g., aggregates of zip codes, census tracts) with population attributes. They could be smaller in densely populated areas with large pollutant gradients. Each CMZ would ideally equal the collective zone of representation of one or more community-oriented monitors within that zone. The CMZ, applicable only to  $PM_{2.5}$ , is intended to represent the spatial uniformity of  $PM_{2.5}$  concentrations. In practice, more than one monitor may be needed within each CMZ to evaluate the spatial uniformity of  $PM_{2.5}$  concentrations and to accurately calculate the spatial average for comparison with the annual  $PM_{2.5}$  NAAQS. When spatial averaging is used, each MPA would be completely covered by one or more contiguous CMZs.

### 2.3.3 Monitoring Networks

$PM_{2.5}$  monitoring networks may be new networks or part of existing networks. Additional sites may be added to existing networks according to this guidance.

- **State and Local Air Monitoring Stations (SLAMS):** SLAMS are designed and operated by local air pollution control districts to determine: 1) the highest concentrations expected to occur in each MPA; 2) representative concentrations in areas of high population density; 3) the impact on ambient pollution levels of significant sources or source categories; 4) general background concentration levels; 5) the extent of regional pollutant transport among populated areas, and 6) welfare-related impacts in rural and remote areas (i.e., visibility impairment and effects on vegetation). Only population-oriented SLAMS acquire data for determining compliance with PM<sub>2.5</sub> standards, and community-oriented (core) SLAMS acquire data for compliance with the annual PM<sub>2.5</sub> standard.
- **National Air Monitoring Stations (NAMS):** NAMS are long-term monitors to assess trends and support national assessments and decisions. The NAMS are intended to be part of a national trends network focusing on community exposure surveillance. NAMS is a subset of SLAMS, with the majority of sites being used to determine compliance or non-compliance with standards. Existing PM<sub>10</sub> NAMS should generally be good candidates for PM<sub>2.5</sub> monitoring.
- **Photochemical Assessment Monitoring Stations (PAMS):** PAMS track trends in ozone precursor emissions, corroborate emission inventories, and support photochemical modeling. Ozone non-attainment areas classified as serious, severe, or extreme have PAMS sites that include enhanced monitoring of ozone, ozone precursors, and surface and upper-air meteorology. PAMS site type 2 represent the area of maximum O<sub>3</sub> precursor concentration and should also represent good locations for core PM<sub>2.5</sub> sites. Though PAMS site type 1 and 4 are intended to be used for regional-scale ozone assessment, their siting and measurements also apply to secondary nitrate and organic aerosol formation and they should be considered as potential PM<sub>2.5</sub> monitoring sites, especially for transport and background monitoring. MPAs with existing PAMS are to install a PM<sub>2.5</sub> core site at a minimum of one PAMS location.
- **Interagency Monitoring of Protected Visual Environments (IMPROVE):** As noted above, the IMPROVE network provides long-term measurements of PM<sub>2.5</sub> and other visibility-related observables in National Parks and Wildernesses throughout the U.S. IMPROVE sites, and the data acquired at those sites, may qualify as background and/or transport sites for PM<sub>2.5</sub> networks.

#### 2.3.4 Site Types

Several types of sampling sites, not all of which are designated for determining compliance with NAAQS, will be part of the PM<sub>2.5</sub> measurement networks.

- **Community-Oriented (Core) Sites:** Community-oriented sites are located where people live, work, and play rather than at the expected maximum impact point for specific source emissions. These sites are not located within the microscale or middle-scale zone of influence of a specific, nearby particle emitter. Community-

oriented sites may be located in industrial areas as well as and in residential, commercial, recreational, and other areas where a substantial number of people may spend a significant fraction of their day.

A subset of the core sites are intended to acquire  $PM_{2.5}$  concentrations every day. These include core SLAMS sites and sites collocated with PAMS sites. Two or more such core sites are to be operated in MSAs with population greater than 500,000, with at least one additional core site in each PAMS area.

Core sites are used to determine NAAQS compliance for both annual and 24-hour  $PM_{2.5}$  standards. Because core sites are the only sites eligible for comparison to both the annual and 24-hour  $PM_{2.5}$  NAAQS, they are the most important sites in the new  $PM_{2.5}$  network.  $PM_{2.5}$  concentrations may be spatially averaged among these sites within a CMZ when the annual average  $PM_{2.5}$  at each core site is within  $\pm 20\%$  of the spatial average on a yearly basis. Core sites should have a zone of representation of at least neighborhood scale ( $> 0.5$  km). For a neighborhood scale, this means that the 24-hour concentrations should vary by no more than  $\pm 10$  percent within an area whose diameter is between 0.5 and 4 km. For urban scale, the concentrations would be similar for distances greater than 4 km. In some monitoring areas, a site with a smaller spatially representative scale (microscale or middle scale) may be representative of many such small scale sites in the general area. This site is effectively representative of a larger scale and in accordance with Appendix D to 40 CFR 58 is also eligible to be called a core site. Sites representing source areas with small zones of influence (e.g., less than one-tenth the dimensions of the CMZ) do not qualify for spatial averaging.

The state can use one or more core monitoring sites to define community air quality for purposes of making comparisons to the annual  $PM_{2.5}$  NAAQS. Multiple sites would exist within community monitoring zones and must each meet the eligibility requirements of Appendix D to 40 CFR 58. The elected community monitoring approach and the description of the CMZs would be contained in the state's network description.

- **Daily Compliance Sites:** Daily compliance sites are used to determine NAAQS compliance for the 24-hour (daily)  $PM_{2.5}$  standard, but not for the annual standard. Because a daily compliance site does not necessarily represent community-oriented monitoring, it may be located near an emitter with a microscale or middle-scale zone of influence.

The PM monitoring regulations state that any population-oriented site is eligible for comparison to the 24-hour  $PM_{2.5}$  standard. If the monitoring site is also representative of community-wide air quality, it is eligible for comparison to the annual  $PM_{2.5}$  NAAQS. With a few anticipated exceptions, almost all sites in the new network will be population-oriented. A site may be population-oriented and at the same time be source oriented or reflective of maximum concentration. The same is true for the existing  $PM_{10}$  network.

Population-oriented sites may be located in hot spot locations and other portions of the above areas which are likely to invoke exposure to fine particles for at least part of a 24-hour sampling period. Hot spot locations have a micro or middle measurement scale of representativeness. Microscale means that the 24-hour measurements should vary by no more than  $\pm 10\%$  within a circle of diameter 100 meters. Middle scale means that the 24-hour measurements should vary no more than  $\pm 10\%$  within a circle of diameter 100-500 meters. These distances are the area around the monitor which may be different than the distance to the nearest major influencing source.

Limitations in resources dictate some tradeoffs in the selection of hot spot locations. Every potential hot spot may not be covered. In general, those maximum concentration locations most reflective of larger population impact should be given higher priority in the placement of permanent monitoring stations. Restrictions in the ability to site permanent monitors is also an important consideration. It may not be feasible to always establish stations adjacent to occupied buildings and within recreational settings, because we cannot obtain permission to use the property or the buildings obstruct the air flow. In such cases, alternate locations which are representative of population-oriented sites should be considered.

- **Special Purpose Monitors (SPM):** SPMs may or may not be used to determine compliance. Their purpose is to understand the nature and causes of excessive concentrations measured at compliance monitoring sites. SPMs do not necessarily use FRMs or FEM methods, and they may be operated over short periods of time at different locations. SPMs may be discontinued within their first two years of operation without prejudice when their purpose has been achieved. Typical SPMs might include: 1) portable saturation monitors operated at many locations around core sites to determine zones of representation, zones of influence, and spatial uniformity; 2) sequential samplers with Teflon and quartz filters or absorbing substrates to determine diurnal distributions of PM-chemical components and precursor gases; and 3) short-time-resolution continuous monitors to determine diurnal mass concentration changes in response to changes in emission rates and meteorology. When SPMs use FRM or FEM samplers and satisfy other requirements of section 58.14a, then they may be used to judge compliance. However, non-attainment designations will not be based upon the SPM data for the first two years of their operation.
- **Transport Sites:** Transport sites are intended to assess the effects of emissions within one MPA or isolated emission sources on other MPAs. To do this, they are typically located between MPAs, or between non-urban source areas and MPAs. Meteorological measurements will usually be associated with transport sites.
- **NAMS Sites:** Subsets of core and transport sites will be selected for long-term monitoring and will be designated as  $PM_{2.5}$  NAMS for assessing trends and for performing future epidemiological studies.

- **Background Sites:** Background sites are intended to represent regional-scale PM<sub>2.5</sub> concentrations that may be a combination of contributions from several MPAs and non-urban source areas, as well as natural emissions. These are usually located in pristine areas, such as National Parks and Wilderness areas, and possibly at elevations higher than MPAs, but still within the typical mixed layer of the atmosphere.

## 2.4 Network Design Philosophies

The design of environmental sampling networks has been studied in hydrology (Andricevic, 1990; Kassim and Kottegoda, 1991; Woldt and Bogardi, 1992; Meyer *et al.*, 1994), meteorology (Gandin, 1970), and the geological sciences (Camisani-Calzolari, 1984; de Marsily *et al.*, 1984; Russo, 1984). Only a few of these concepts have been adapted to air quality networks. Some of the earliest work done in network design focused on meteorological observations (Gandin, 1970).

### 2.4.1 Network Design Objectives

Networks are designed to attain specific objectives. Objectives of the SLAMS PM<sub>2.5</sub> monitoring network are (U.S. EPA, 1997b):

- To determine representative concentrations in areas of high population density.
- To determine the impact on ambient pollution levels of significant sources or source categories.
- To determine general background concentration levels.
- To determine the extent of regional pollutant transport among populated areas; and in support of secondary standards.
- To determine the highest concentrations expected to occur in the area covered by the network.
- To determine the welfare-related impacts in more rural and remote areas such as visibility impairment and effects on vegetation.

Munn (1981) defines two basic methods of network design: 1) the statistical method, and 2) the modeling method. The statistical method assumes that existing data is available to extract meaningful statistical information for network design.

The statistical approach is based on the lognormal distribution followed by most air quality data (Larsen, 1969; Noll and Miller, 1977). Statistical methods take advantage of the fact that most air quality measurements are correlated either in time at the same location or in space with other monitors in a network. Networks are optimized by examining time series correlations from long measurement records or spatial correlations among measurements

from many nearby monitors (Munn, 1975; Elsom, 1978; Handscombe and Elsom, 1982). Munn (1981) identifies four types of correlation analysis: 1) time correlation (autocorrelation) at one site; 2) cross-correlation of several pollutant concentrations at one site; 3) spatial correlations among simultaneous measurements at different sites; and 4) spatial correlations among different sites with time lags.

#### 2.4.2 Random Sampling

Random sampling locates sites by chance, without taking into consideration the sources of pollutants (Nesbitt and Carter, 1996). Random placement is accomplished by specifying boundaries of a rectangular domain, generating x and y coordinates from a uniform-distribution random number generator truncated at the domain boundaries, and placing samplers as close to these coordinates as practical.

The advantages of random sampling designs are: 1) measurement bias is minimized; 2) implementation simplicity, with no knowledge assumed about the spatial and temporal distribution of concentrations; and 3) sampling locations are objectively chosen. The disadvantages are that: 1) many sampling locations must be allocated for an acceptable sampling error; 2) there is large potential for redundancy in a network with many locations; and 3) there is a large risk of poorly representing exposures in a network with few locations.

Borgman *et al.* (1996) cites an example of how many samplers are required for a certain confidence interval. If the 95% confidence interval is  $1 \mu\text{g}/\text{m}^3$  with a variance,  $\sigma^2$ , of  $6.5 (\mu\text{g}/\text{m}^3)^2$  the estimated number of samples is found to be

$$\frac{1.96\sigma}{\sqrt{n}} = 1$$

and solving for n yields 25 samples. This large number of PM sampling sites would only be applicable to a very large urban area, or for a short-term special-study.

From a practical standpoint, random network siting is not a useful model for air quality monitoring. Prior knowledge, though sometimes incomplete, is always available concerning the sources and meteorology that affect PM concentrations in an area. Sampler siting constraints of power, security, and minimum separations from nearby emitters and obstructions impose logistical constraints that prevent a purely "random" selection of measurement locations. The community exposure monitoring philosophy of the new standards is not served by a random-sampling network design.

#### 2.4.3 Systematic Sampling

Systematic sampling locates samplers on a grid system, with one sampler assigned to each grid cell. Noll and Miller (1977) call this type of sampling the "area method". This method is most applicable in flat terrain with a few large point sources. Samplers are placed as close to the center of the cell as practical. This method minimizes sampling bias because of its regular spacing of sensor locations. However, systematic sampling requires a

substantial number of samplers depending on the size of the MPA, and most of these samplers supply redundant information where PM<sub>2.5</sub> concentrations are spatially uniform.

Systematic sampling costs may be prohibitively high, even for small areas, except for short periods during which spatial uniformity is being evaluated. The positive characteristic of systematic sampling is that the network completely covers the planning area.

#### 2.4.4 Judgmental Sampling

Judgmental sampling (Nesbitt and Carter, 1996) uses knowledge of source emissions and sensitive receptor locations, coupled with mechanisms for pollutant transport, to locate measurement sites. Noll and Miller (1977) call this the "source orientation method" and deem it most appropriate for monitoring point sources in uneven terrain. Air pollution models can be used to assist in this judgment, but this requires exceptional accuracy of the model formulation and the model input data. Few areas in the U.S. have good estimates of particle and precursor gas emissions, especially from mobile and area sources. Complex terrain and meteorology, as well as simulating secondary aerosol formation, also present challenges to currently available models for suspended particles.

Judgmental sampler locations may be determined by data from an existing monitoring network or by identifying the locations of pollutant sources and inferring pollutant transport from data analysis of emissions and wind measurements. Short-term experiments involving spatially dense measurements and modeling may assist in making or verifying judgments.

Monitoring networks for criteria pollutants always use judgmental sampling strategies that consider where source emissions are in relation to populations and which way the wind blows.

#### 2.4.5 Heterogeneous Siting Strategies

Nesbitt and Carter (1996) combine judgmental and systematic sampling by applying the following steps: 1) identify potential sources of contamination or "hot spots" using existing measurements or models; 2) place a grid system over these areas; 3) perform sampling at these grid points; 4) define a systematic grid at points which yield positive contamination; 5) use the systematic grid to assess the remainder of the study area.

Figure 2.4.1 shows how a judgmental strategy compares with a combined judgmental and systematic strategy. The concentration isopleths can be interpolated from spatially dense measurements or produced by an air quality model. The judgmental strategy, by itself, missed areas of significant concentrations, while the combined judgmental and systematic strategy covered the areas of significant concentration that had not previously been monitored.

Another hybrid method for locating potential particulate matter samplers is based on geostatistical sampling (Journel, 1980; Russo, 1984; Kassim and Kottegoda, 1991; Trujillo-Ventura, 1991; Rouhani *et al.*, 1992; Borgman *et al.*, 1996). Kriging is a common method for interpolation to predict unknown values from existing spatial data (Volpi and



# Network Design and Site Selection for Monitoring PM<sub>2.5</sub> and PM<sub>10</sub> in Ambient Air

## Quiz 1

**Directions:** Take this quiz to determine whether you have mastered the objectives of Lessons 2 and 3 before you take the final exam.

Do not use your notes or books. Take no more than 30 minutes to complete the quiz. Check your answers against the answer key in Appendix B. Review the materials for any questions you may have missed.



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1. The NAAQS primary standard for  $PM_{2.5}$  is
  - a.  $15\mu\text{g}/\text{m}^3$  as an annual arithmetic mean from a single community-oriented monitoring site and  $50\mu\text{g}/\text{m}^3$  for a 24 hour average of a 3 year average of annual 99<sup>th</sup> percentiles.
  - b.  $15\mu\text{g}/\text{m}^3$  as an annual geometric mean from a population-oriented monitoring site and  $50\mu\text{g}/\text{m}^3$  for a 24 hour average of a 3 year average of annual 98<sup>th</sup> percentiles.
  - c.  $15\mu\text{g}/\text{m}^3$  as an annual arithmetic mean from a single or multiple community-oriented monitoring site and  $65\mu\text{g}/\text{m}^3$  for a 24 hour average of a 3 year average of annual 98<sup>th</sup> percentiles.
  - d.  $15\mu\text{g}/\text{m}^3$  as an annual geometric mean from a population-oriented monitoring site and  $65\mu\text{g}/\text{m}^3$  for a 24 hour average of a 3 year average of annual 99<sup>th</sup> percentiles.
  
2. True or False? One of the NAAQS for mass concentrations of particulates with an aerodynamic diameter lower than  $2.5\mu\text{m}$  is a 24-hour average of  $PM_{2.5}$  not to exceed  $50\mu\text{g}/\text{m}^3$  for a 3 year average of annual 98<sup>th</sup> percentiles at any population-oriented monitoring site in a monitoring area.
  - a. True
  - b. False
  
3. One of the NAAQS for mass concentrations of particulates with an aerodynamic diameter lower than  $10\mu\text{m}$  is a 24-hour average of  $PM_{10}$  not to exceed \_\_\_\_  $\mu\text{g}/\text{m}^3$  for a 3 year average of annual \_\_\_\_ percentiles any monitoring site in a monitoring area.
  - a. 50, 98<sup>th</sup>
  - b. 50, 99<sup>th</sup>
  - c. 150, 98<sup>th</sup>
  - d. 150, 99<sup>th</sup>

4. One of the NAAQS for mass concentrations of particulates with an aerodynamic diameter lower than  $2.5\ \mu\text{m}$  is a 24-hour average of  $\text{PM}_{2.5}$  not to exceed \_\_\_\_  $\mu\text{g}/\text{m}^3$  for a 3 year average of annual \_\_\_\_ percentiles at any population-oriented monitoring site in a monitoring area.
- 50, 98<sup>th</sup>
  - 50, 99<sup>th</sup>
  - 65, 98<sup>th</sup>
  - 65, 99<sup>th</sup>
5. The new network design and siting requirements encourages the placement of  $\text{PM}_{2.5}$  monitors outside population centers in more rural areas
- to provide the air quality data necessary to facilitate implementation of the NAAQS
  - to augment the existing visibility fine particle monitoring network.
  - both a and b.
  - neither a nor b.
6. The EPA requires States to archive collected  $\text{PM}_{2.5}$  filters because the EPA will need the filters to
- help identify PM emission sources.
  - develop effective control programs.
  - both a and b
  - neither a nor b
7. Which of the following EPA documents provides information and guidance about the validity of data and the accuracy of measurement systems?
- Guidance for the Network Design and Optimum Site Exposure for  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$ .*
  - Guidance for the Sampling and Analysis for  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$ .*
  - Guidance for the Continuous Monitoring for  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$ .*
  - Quality Assurance Handbook for Air Pollution Measurement Systems, Volume IV: Meteorological Measurements*

8. The nucleation range consists of particle sizes with a diameter
- less than 0.08  $\mu\text{m}$ .
  - between 0.08  $\mu\text{m}$  and 2  $\mu\text{m}$ .
  - 2  $\mu\text{m}$  and 10  $\mu\text{m}$ .
  - greater the 10  $\mu\text{m}$ .
9. The resident lifetime for particles in the nucleation range is usually
- less than 1 hour.
  - from 1 to 12 hours.
  - from 12 to 24 hours.
  - greater than 24 hours.
10. The accumulation range consists of particles with a diameter
- less than 0.08  $\mu\text{m}$ .
  - from 0.08  $\mu\text{m}$  to 2  $\mu\text{m}$ .
  - from 2  $\mu\text{m}$  to 10  $\mu\text{m}$ .
  - greater the 10  $\mu\text{m}$ .
11. Which of the following is **NOT** a characteristic property of secondary particles?
- Secondary particles usually form over several hours or days.
  - Secondary particles form in the atmosphere from gases that are directly emitted by gases.
  - Ambient concentrations of secondary particles are proportional to quantities of emissions.
  - Secondary particles usually attain aerodynamic diameters between 0.1 and 1.0  $\mu\text{m}$ .
12. True or False? Determining the concentration of secondary pollutants at a specific source is an objective of PM network design.
- True
  - False

13. \_\_\_\_\_ monitors are usually placed in pristine areas and used to represent PM emissions on a regional scale.
- a. NAMS
  - b. Transport
  - c. Background
  - d. Special purpose
14. Non-attainment designations will not be based upon special purpose monitor data for the first \_\_\_\_\_ years of operation.
- a. one
  - b. two
  - c. three
  - d. four
15. \_\_\_\_\_ monitoring sites can be used to define community air quality for purposes of making comparisons to annual PM<sub>2.5</sub> NAAQS.
- a. Core
  - b. Transport
  - c. Special purpose
  - d. Daily Compliance

## **Required Readings**

## **Answers to Quiz 1**

1. c
2. b
3. d
4. c
5. c
6. c
7. d
8. a
9. a
10. b
11. c
12. b
13. c
14. b
15. a

# APPENDIX A

## *Answers to Review Exercises*



## Lesson 2

1. a
2. b
3. d
4. c
5. c
6. d
7. a
8. b
- 9.

- define concepts and terms of network design.
- summarize the availability and usage of existing resources for network design.
- demonstrate the methodology in practical applications.
- present a methodology for defining planning areas and selecting and evaluating monitoring sites in a network.

10.

- Twenty-four hour average  $PM_{2.5}$  not to exceed  $65 \mu\text{g}/\text{m}^3$  for a three-year average of annual 98<sup>th</sup> percentiles at any population-oriented monitoring site in a monitoring area.
- Three-year annual average  $PM_{2.5}$  not to exceed  $15 \mu\text{g}/\text{m}^3$  concentrations from a single community-oriented monitoring site or the spatial average of eligible community-oriented monitoring sites in a monitoring area.
- Twenty-four hour average  $PM_{10}$  not to exceed  $150 \mu\text{g}/\text{m}^3$  for a three-year average of annual with percentiles at any monitoring site in a monitoring area.
- Three-year average  $PM_{10}$  not to exceed  $50 \mu\text{g}/\text{m}^3$  for three annual average concentrations at any monitoring site in a monitoring area.

## Lesson 3

1. less than  $0.08 \mu\text{m}$
2. from  $0.08 \mu\text{m}$  to  $2.5 \mu\text{m}$
3. greater than  $2.5 \mu\text{m}$

4. d

5. c

6. d

7. b

8. a

9.

- To determine representative concentrations in areas of high population density.
- To determine the impact on ambient pollution levels of significant sources or source categories.
- To determine general background concentration levels.
- To determine the extent of regional pollutant transport among populated areas; and in support of secondary standards.
- To determine the highest concentrations expected to occur in the area covered by the network.
- To determine the welfare-related impacts in more rural and remote areas such as visibility impairment and effects on vegetation.

10. c

11. b

12. a

13. f

14. e

15. b

16. a

17. d

18. a