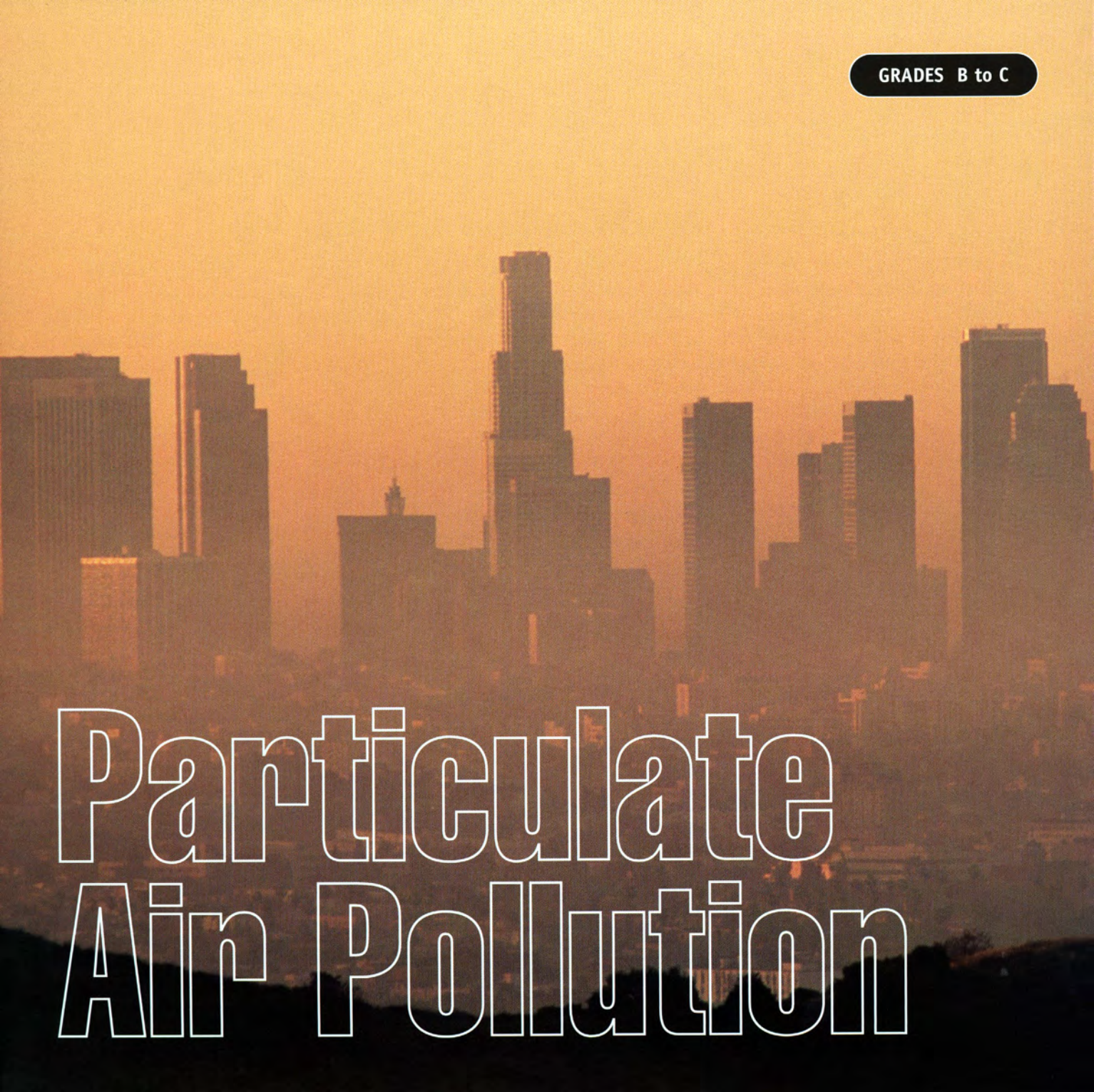


GRADES B to C



Particulate Air Pollution

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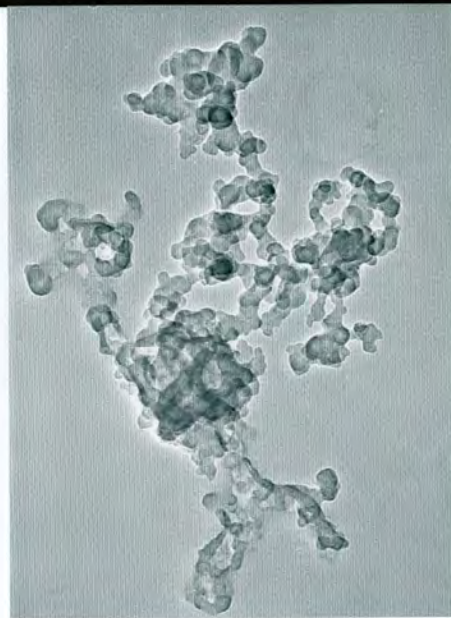
INTRODUCTION

On a typical day in Southern California the average person outdoors inhales more than 10 million microscopic and submicroscopic particles with each breath. Indoors concentrations may as much as ten times higher, or they may be lower than outdoor concentrations. The particles are emitted from motor vehicles, especially diesel vehicles, and industrial sources; resuspended by the wind; or formed in the atmosphere from gaseous pollutants. Atmospheric particles occur in a wide range of sizes and shapes; some are droplets and some are solid. Although individual particles are invisible to the unaided eye, the collective effect of high concentrations of these particles in the ambient environment can be a dramatic reduction in visibility. In fact only these airborne particles, or particulate pollution, significantly affects visibility in the Los Angeles basin. Gaseous pollutants play a minor role in visibility reduction, although nitrogen dioxide can contribute to a yellowish color in the atmosphere.

Only in the past 10 years have we begun to understand the magnitude of the health effects associated with particulate air pollution. Historically airborne particles were considered more of a nuisance than a health

risk. Early regulations restricted visible plumes from smokestacks and were concerned about soot and soiling. Particles were not perceived as causing any "acute" health effects and thus were not controlled as stringently as sulphur dioxide, carbon monoxide, or ozone and its precursors.

The effects of airborne particles on visibility and health depend on the size of the particles and their chemical composition. However, current air quality standards for particulate matter do not distinguish between particles of different chemical composition, and only with the introduction of PM-10 sampling in 1987 was particle size featured in the monitoring of particulate air pollution. PM-10 refers to particles less than 10 micrometers (μm) in size. A micrometer is a thousandth of a millimeter or about a fiftieth of the width of the finest human hair. It would take approximately 130,000 1-micrometer particles to cover the dot over this "i." The use of PM-10 sampling and air quality standards helped reveal health effects of particulate matter that were obscured by earlier and less precise sampling methods. Recently new air quality standards and sampling methods have been implemented to focus on PM-2.5, particulate matter less than 2.5 micrometers. But cur-



Typical atmospheric soot particles.

rently there is debate concerning which particle size fraction best reflects the health risk to the public.

This article reviews the increasingly important role of particle size in our understanding of the health effects of particulate air pollution, the sources and trends in ambient levels of airborne particles in Southern California, and current research findings on particulate pollution health effects.

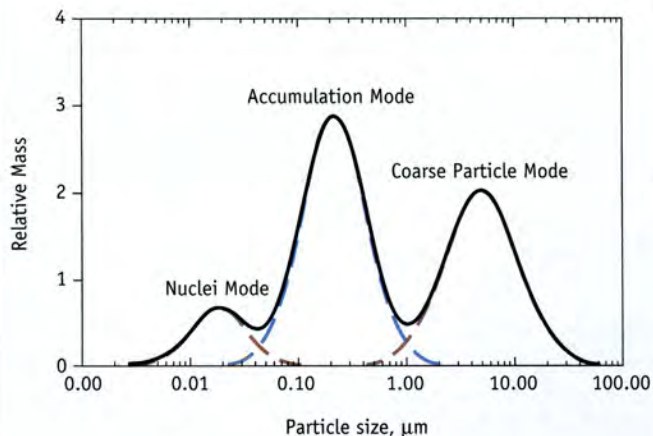


Figure 1: Typical urban particulate matter size distribution.

ROLE OF PARTICLE SIZE

Figure 1 shows the distribution of particle sizes typically found in urban environments. Although the particles are all mixed together in the air, we characterize them as occurring in three well-defined modes: the nuclei, accumulation, and coarse particle modes. The particles in each mode have different sources and chemical compositions. The nuclei and accumulation modes together constitute *fine particles*, or *fine particulate matter*. The shape of the particle size distribution shown in Figure 1 is multimodal, having more than one peak, because it represents a mixture of particles from many different sources whose size distributions have been modified by growth processes, evapora-

tion and removal mechanisms that favor one particle size range over another. These very fine particles attach rapidly to particles in the accumulation mode.

The *accumulation mode* includes combustion and photochemical smog particles and attached nuclei mode particles. Removal mechanisms, such as settling, deposition to surfaces, or attachment to rain droplets, are weak for this size range. The accumulation mode particles are about the same size as the wavelength of visible light, consequently these particles scatter and absorb visible light and account for most of the visibility effects of urban particulate pollution.

Transportation, including motor vehicles and paved road dust, accounts for about 40% of PM-10 in the Los Angeles area.

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The *nuclei mode* consists primarily of combustion particles emitted directly into the atmosphere from motor vehicles, especially diesel vehicles, as well as particles

The *coarse-particle mode* consists of windblown dust, salt particles from sea spray, and mechanically generated particles such as from construction sites. These large particles settle out relatively quickly and so have lifetimes in the atmosphere of hours. Fine and coarse particles have quite different chemical compositions, sources, and lifetimes in the atmosphere, and there is little mass exchanged between the particles in these two modes.

Particle size is important for health because it controls where in the respiratory system a given particle deposits (see Figure 2). Particles as large as a few micrometers are able to reach and deposit in the sensitive, gas-exchange region of the lung (also called the alveolar region or deep lung) where they are removed slowly. Some fraction of inhaled particles larger than about 2 micrometers deposit in the airways leading to the gas exchange region. These airways are “self-cleaning” tubes that remove deposited particles in a few hours. Specifically, these airways are lined with a layer of mucous that is constantly migrating to the back of the throat where it is swallowed. The rapidly cleared regions, including the nose, throat, and airways, serve to protect the more vulnerable gas exchange region. While exercise changes the pattern of deposition

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somewhat, the more important factor is the greater volume of air inhaled when exercising, up to five times as much as when at rest.

SOURCES

Figure 3 shows the relative importance of the different sources of PM-10 particulate matter. Transportation, including motor vehicles and paved road dust, is the most important

source of PM-10 in the Los Angeles area, accounting for about 40% of PM-10. Particles formed photochemically in the atmosphere from *gaseous* motor vehicle and industrial emissions account for about 20% of PM-10, with nearly all occurring in the May through October summer period in the Los Angeles basin.

Airborne particles are divided into primary particles, those that are emitted direct-

ly into the atmosphere, and secondary particles, those that are formed in the atmosphere by chemical reactions of gases and vapors from various sources. Stationary emission sources are primarily smokestack industries that have been the focus of control efforts for many years. Household sources are associated with home activities, such as home heating, barbecuing, wood fireplace fires, and lawn mowing. These have come under increased attention as other sources have been controlled. Emissions, such as dust from dirt roads, resuspended tire dust from paved roads, and wind blown dust from arid land, are primarily in the coarse particle mode. They are heavily dependent on meteorological conditions.

The most important sources of particles in Southern California are motor vehicles, including cars, trucks and buses, often referred to as mobile sources. Controls on gasoline-powered vehicles, such as catalytic converters, improved engine design, reformulated gasoline, and evaporative emissions controls, have been in use for many years. These controls have substantially reduced both direct particle emissions from gasoline powered vehicles and the emission of hydrocarbon and oxides of nitrogen (NO_x) gases that contribute to secondary particle formation.

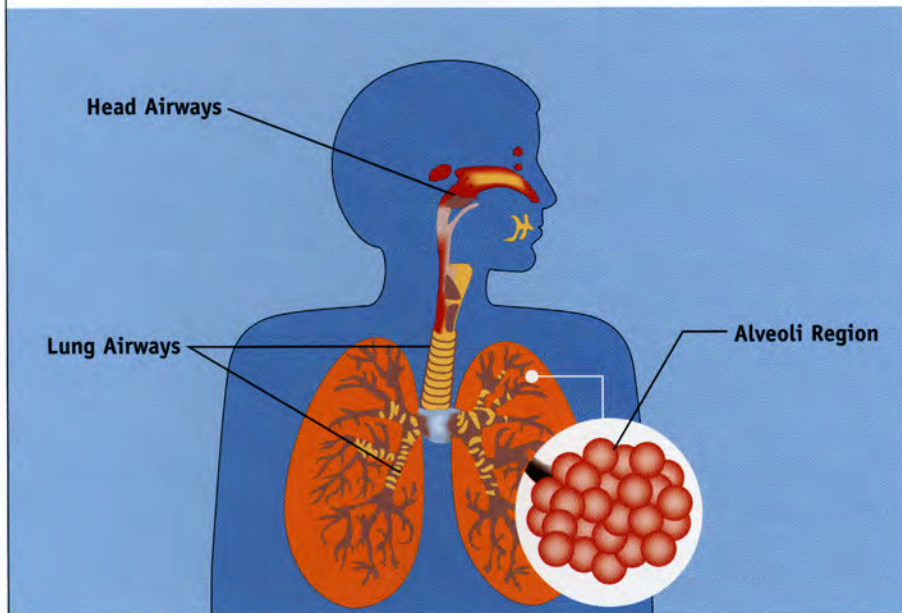
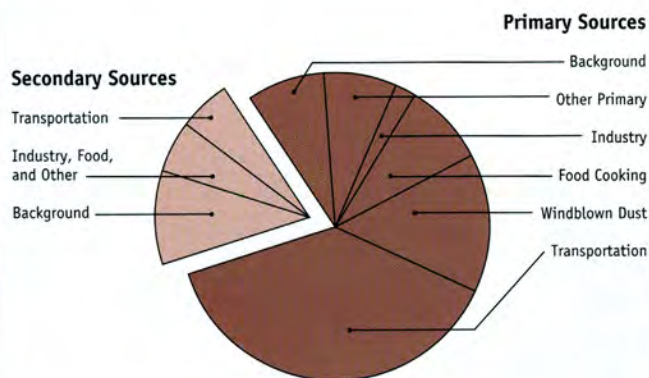


Figure 2: Human respiratory system.

The Federal standard for PM-2.5 is exceeded at 15 of 16 monitoring sites in the Los Angeles basin.



Source: Kleeman and Cass, Atmos. Env. Vol. 32, pp. 2803 (1998)

Figure 3: Sources of PM-10 in the Los Angeles area.

Similar approaches are now being undertaken for diesel powered vehicles. Diesel vehicles are major emitters of fine particulates, including soot, a major source of polycyclic aromatic hydrocarbons (PAHs), which are potential cancer causing materials. The South Coast Air Quality Management District (AQMD) estimates that currently diesel-powered motor vehicles are responsible for a substantial portion of the cancer risk from mobile sources in the Los Angeles basin.

As noted above, secondary particles include particles formed by gas-to-particle conversion, that is by chemical reactions in the atmosphere, such as the conversion of nitrogen dioxide to nitrate particles. Thus secondary particles are one component of photochemical smog formed by the action of strong sunlight on hydrocarbon vapors and

and 70s by the concerted efforts of governments and citizens over the past three decades, there has not been as significant a reduction in particulate levels.

TRENDS IN AMBIENT LEVELS

Currently the annual average concentration of PM-10 in the South Coast Air Quality Management District exceeds the Federal air quality standard at eight of the 21 monitoring sites. For PM-2.5 the Federal standard is exceeded at all but one of 16 monitoring sites. Figure 4 shows the trend in the percent of days each year the Los Angeles basin has exceeded the Federal standard for PM-10 since 1985. The improvement observed over this period is a result of the control of industrial and motor vehicle sources, discussed

above, and the reduction in emissions of hydrocarbons and oxides of nitrogen, the precursors of photochemical smog.

NO_x. As discussed in RC 1998, photochemical smog has been a problem in the Los Angeles region for many years. However, while compounds such as ozone have been reduced about 65% from peak levels in the 1960s

above, and the reduction in emissions of hydrocarbons and oxides of nitrogen, the precursors of photochemical smog.

California has the highest per capita motor vehicle ownership of any state or nation and the steady progress in the control of particulate air pollution is remarkable considering the large increase in motor vehicles and vehicle miles traveled since 1985. This trend in lower particle concentration is expected to continue with the introduction of emission controls on diesel powered vehicles and the decrease in the number of high-emitting vehicles from our roads over the next few years. High emitting vehicles are passenger cars that, because of age, poor maintenance or faulty pollution control equipment, emit abnormally high amounts of pollutants, especially carbon monoxide and particles. These high-emitting vehicles represent less than 10% of the vehicles on the road, but produce 90% of the particulate emissions from passenger cars.

The State of California in conjunction with 13 other states has adopted a plan to reduce diesel emissions by 75% by 2010. The plan includes requirements for lowering the sulfur content of diesel fuel by 97%, retrofitting existing diesel engines with particulate filters, and a 90% reduction of par-

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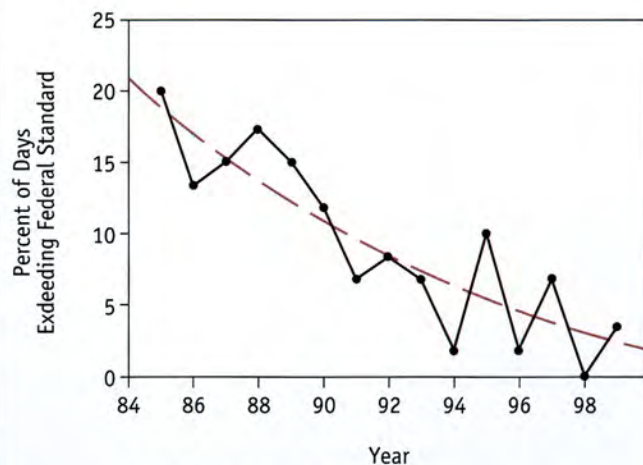
ticulate emissions from new diesel vehicles. These requirements would be phased in starting in 2002.

In general the finer the particles the more difficult they are to control. A substantial reduction in total suspended particulate (TSP) or PM-10 may result in a negligible reduction in PM-2.5. While the Los Angeles basin meets the PM-10 (24-hour) standard more than 95% of the time, meeting the standard for PM-2.5 will be much more difficult. Currently, about two-thirds of the Los Angeles basin meets the annual average for PM-10, but most of the basin exceeds the annual average PM-2.5 standard of $15 \mu\text{g}/\text{m}^3$. The maximum 24-hour and annual average PM-2.5 concentrations in the Los Angeles basin are about two times the corresponding Federal standard. These fine particles cannot be easily filtered out of vehicle exhaust and will require changes in engine design and fuels to meet the standards in the Los Angeles basin. Furthermore, the secondary particles formed in the atmosphere are also primarily in the PM-2.5 size range.

HEALTH EFFECTS

The early focus for health risk from particulate air pollution was on chronic

conditions such as lung cancer. That shifted in the 1990s when data from PM-10 sampling became available to health effects researchers. The greater precision and specificity of PM-10 data allowed epidemiologists to distinguish health effects of particulate air pollution that were masked by the variability and dominance of large particles of TSP sampling. Some studies have shown that cities with higher particulate air pollution experience more respiratory disease than cities with lower levels. This is especially true when PM-2.5 concentration is used instead of PM-10 concentration as a measure of particulate air pollution. These studies, however, were conducted in cities in the East and Midwest which have particles of different chemical compositions than those found in the Los Angeles basin. Some studies have estimated that particulate air pollution in the United States causes an average loss of life expectancy of one to three years. Other studies have found an



Source: South Coast Air Quality Management District

Figure 4: Trend in the annual percent of days exceeding the Federal PM-10 standard (24-hour) in the Los Angeles basin, 1986-1999.

association between PM-10 and increases in infant mortality from respiratory causes.

A critical finding is that daily increases in particulate air pollution are associated with increases in hospital admissions and mortality. This holds true for mortality due to respiratory disease and cardiovascular disease, and also holds true for a wide range of cities throughout the U.S. with different climates and pollution mixes. In Southern California this effect has been observed in Los Angeles, San Bernardino, and Santa Ana-Anaheim. It also holds true for particulate air pollution levels that are less than the current standards for PM-10. An analysis by the Natural Resources

History of PM Air Quality Standards

Air quality and sampling standards for particulate matter in the United States were first set in 1971. The standard sampling method collected what is known as *total suspended particulate (TSP)* by sampling with a high-volume (hi-vol) sampler that drew air through a large filter at about 50 cubic feet per minute. The air quality standard required an annual average concentration of less than 75 micrograms of particulate per cubic meter of air ($\mu\text{g}/\text{m}^3$). A microgram is a millionth of a gram or about one-tenth the weight of a single eyelash. Particulate matter standards, unlike those for other criteria pollutants, are not specific to a particular chemical, but simply specify the particulate mass concentration regardless of chemical composition. The sampling pump and filter used for TSP sampling were enclosed in a peaked-roof enclosure to protect it from the weather. The filter had high efficiency for all particle sizes, but the enclosure caused a variable collection efficiency of larger sized particles, those in the range from 20 to 50 micrometers, that was dependent on wind velocity and direction. This gave variable measurements of

particulate mass concentration that did not reflect the health risk to humans.

To overcome this problem US EPA promulgated PM-10 ambient air quality standards and sampling criteria in 1987. Particles that meet the PM-10 criteria are those less than 10 micrometers (μm) and represent a portion of the TSP particles. An aerodynamic separator in the sampler inlet selects those particles that meet the PM-10 criteria while they are still airborne. The PM-10 standard requires communities to achieve an annual average concentration of PM-10 particles of less than 50 $\mu\text{g}/\text{m}^3$. PM-10 sampling has two advantages: a well defined upper limit which is not affected by wind velocity or direction; and a well defined health basis, namely collection of particles able to pass through the mouth, nose and throat and reach the lungs. This more precise type of measurement permitted the discovery of health effects due to particulate air pollution that had been masked by the variability of the TSP method.

One limitation with PM-10 is that the sampled particles contain all of the fine parti-

cle mode and a portion of the coarse particle mode. Because these two modes have different sources and chemical composition it is difficult to separate the role of different chemicals in particulate air pollution and to determine the sources of those particles that cause the health effects, information needed to implement effective control strategies. In 1997 the US EPA adopted additional standards and sampling methods for particles less than 2.5 micrometers, called PM-2.5. The new standard for PM-2.5 is an annual average of 15 $\mu\text{g}/\text{m}^3$. The cutoff at 2.5 micrometers is approximately at the saddle point between the coarse and fine particle modes (see Figure 1) and thus provides samples of fine particles relatively uncontaminated with coarse particles.

The more recent standards defined in terms of particle size can be thought of as a subset or fraction of earlier standards. Thus, PM-2.5 is a subset of PM-10 and PM-10 is a subset of TSP. Each new sampling method focuses in more closely on those particle sizes and chemical compositions that are believed to affect human health.

Defense Council (NRDC) based on these research findings concluded that up to 8,800 people die each year in the South Coast Air Basin as a result of exposure to particulate air pollution. This is about four times the number of people killed in automobile accidents each year in the same region. Other estimates of annual mortality due to particulate pollution in Southern California range from 1,500 to 6,000.

While the elderly are most frequently harmed by increases in particulate levels, other studies in Southern California have found associations between PM-10 levels and increases in asthma episodes and respiratory symptoms and a slowing of the rate of lung growth in children. Although we have learned a great deal about health effects of airborne particles in the past decade, we still do not know what chemical compounds or what aspects of particulate air

pollution are causing these morbidity and mortality effects. To address these serious gaps in our understanding of the health effects of particulate air pollution, the U.S. EPA has established five national research centers to investigate all aspects of urban atmospheric particles, including health effects. One of these centers is based at the UCLA School of Public Health. It also receives research support from the California Air Resources Board.

Daily increases in particulate air pollution are associated with increased hospital admissions and mortality.

CONCLUSION AND ASSESSMENT

Evaluation of progress toward meeting environmental goals for particulate pollution is difficult because of changing standards and, perhaps more important, changing metrics of assessment. Specifically, both the air quality standards and type of measurements used to evaluate progress have changed over the past thirty years. This creates a moving target that

makes evaluation difficult for particulate pollution. Nevertheless, by all of the various metrics, we have made substantial progress in reducing particulate levels despite increases in population and motor vehicles. Until recently, regulators have been slow to crackdown on diesel trucks and buses, but now more stringent regulations are being phased in. These new regulations for diesel motor vehicles, especially for trucks and buses, are expected to continue this improvement in air quality. However, despite this progress, more than one third of the Los Angeles basin exceeds the annual average standard for PM-10. This warrants a grade of **C** for progress in meeting the annual average particulate standards. Furthermore almost all of the region exceeds the annual average standard for PM-2.5, but it is too early to assign a grade to efforts to meet this standard. The commendable reduction in the percent of days exceeding the Federal 24-hour standard, as shown in Figure 4, warrants a grade of **B**.

Because of our uncertainty of the mechanisms of health impacts of particles and changing assessment metrics and standards, only a grade of **Incomplete** can be assigned to our progress in the protection of human health with respect to particulate pollution.



William Hinds has been a Professor in the Department of Environmental Health Sciences and the Center for Occupational and Environmental Health in the UCLA School of Public Health since 1982. Prior to coming to UCLA he was an Assistant and Associate Professor at the Harvard University School of Public Health. Dr. Hinds's research interests include fundamental and applied research related to aerosols (airborne particles) including properties, behavior, and measurement of aerosols, characterization of aerosols for workplace hazard evaluation, respiratory deposition of aerosols, aerosol formation, and aerosol measurement instrumentation; environmental tobacco smoke, performance and evaluation of respiratory protective devices; and industrial control of airborne contaminants. He has more than 80 publications in this field including a standard textbook on aerosol technology. Dr. Hinds received a bachelor's degree in Mechanical Engineering from Cornell University in 1962 and an M.S. and doctorate in Environmental Health in 1969 and 1972 from Harvard University. He is director of the UCLA Industrial Hygiene Program, director of the Southern California NIOSH Education and Research Center, and co-director of the UCLA component of the NIEHS Southern California Environmental Health Center. He is also a member of the EPA Southern California Particle Center and Supersite.

