

Airborne Particulate Matter

Airborne particulate matter, which includes dust, dirt, soot, smoke, and liquid droplets emitted into the air, is small enough to be suspended in the atmosphere. Airborne particulates may be a complex mixture of organic and inorganic substances. They can be characterized by their physical attributes, which influence their transport and deposition, and their chemical composition, which influences their effect on health.

The physical attributes of airborne particulates include mass concentration and size distribution. Ambient levels of mass concentration are measured in micrograms per cubic meter ($\mu\text{g}/\text{m}^3$); size attributes are usually measured in aerodynamic diameter. Particulate matter (PM) exceeding 2.5 microns (μm) in aerodynamic diameter is generally defined as coarse particles, while particles smaller than 2.5 microns ($\text{PM}_{2.5}$) are called fine particles. The acid component of particulate matter, and most of its mutagenic activity, are generally contained in fine particles, although some coarse acid droplets are also present in fog. Samples taken in the United States showed that about 30% of particulate matter was in the fine fraction (Stern et al. 1984).

Particles interact with various substances in the air to form organic or inorganic chemical compounds. The most common combinations of fine particles are those with sulfates. In the United States, sulfate ions account for about 40% of fine particulates and may also be present in concentrations exceeding $10 \mu\text{g}/\text{m}^3$ (USEPA 1982b). The smaller particles contain the secondarily formed aerosols, combustion particles, and recondensed organic and metal vapors. The carbonaceous component of fine particles—products of incomplete combustion—contains both elemental carbon (graphite and soot) and nonvolatile organic carbon (hydrocarbons emitted in combustion ex-

haust, and secondary organic compounds formed by photochemistry). These species may be the most abundant fine particles after sulfates. Additionally, atmospheric reactions of nitrogen oxides produce nitric acid vapor (HNO_3) that may accumulate as nitrate particles in both fine and coarse forms. The most common combination of coarse particles consists of oxides of silicon, aluminum, calcium, and iron.

Terms and Sampling Techniques

Several terms are used to describe particulates. Generally, these terms are associated with the sampling method:

Total suspended particulates (TSP) includes particles of various sizes. Some proportion of TSP consists of particles too large to enter the human respiratory tract; therefore, TSP is not a good indicator of health-related exposure. TSP is measured by a high-volume gravimetric sampler that collects suspended particles on a glass-fiber filter. The upper limit for TSP is 45 microns in diameter in the United States and up to 160 microns in Europe.

TSP sampling and TSP-based standards were used in the United States until 1987. Several countries in Central and Eastern Europe, Latin America, and Asia still monitor and set standards based on measurements of TSP. As monitoring methods and data analysis have become more sophisticated, the focus of attention has gradually shifted to fine particulates. Recent evidence shows that fine particulates, which can reach the thoracic regions of the respiratory tract, or lower, are responsible for most of the excess mortality and morbidity associated with high levels of exposure to particulates. Most sophisticated studies suggest that fine particulates are the sole factor

accounting for this health damage, while exposure to coarse particulates has little or no independent effect.

The particles most likely to cause adverse health effects are the *fine particulates* PM_{10} and $PM_{2.5}$ —particles smaller than 10 microns and 2.5 microns in aerodynamic diameter, respectively. They are sampled using (a) a high-volume sampler with a size-selective inlet using a quartz filter or (b) a dichotomous sampler that operates at a slower flow rate, separating on a Teflon filter particles smaller than 2.5 microns and sizes between 2.5 microns and 10 microns. No generally accepted conversion method exists between TSP and PM_{10} , which may constitute between 40% and 70% of TSP (USEPA 1982b).

In 1987, the USEPA switched its air quality standards from TSP to PM_{10} . PM_{10} standards have also been adopted in, for example, Brazil, Japan, and the Philippines. In light of the emerging evidence on the health impacts of fine particulates, the USEPA has proposed that U.S. ambient standards for airborne particulates be defined in fine particulates.

Black smoke (BS) is a particulate measure that typically contains at least 50% respirable particulates smaller than 4.5 mm in aerodynamic diameter, sampled by the British smokes shade (BS) method. The reflectance of light is measured by the darkness of the stain caused by particulates on a white filter paper. The result of BS sampling depends on the density of the stain and the optical properties of the particulates. Because the method is based on reflectance from elemental carbon, its use is recommended in areas where coal smoke from domestic fires is the dominant component of ambient particulates (WHO and UNEP 1992). After reviewing the available data, Ostro (1994) concluded that BS is roughly equivalent to PM_{10} . However, there is no precise equivalence of the black smoke measurements with other methods. The BS measure is most widely used in Great Britain and elsewhere in Europe.

Sources of Particulates

Some particulates come from natural sources such as evaporated sea spray, windborne pollen, dust, and volcanic or other geothermal eruptions. Particulates from natural sources tend to be coarse. Almost all fine particulates are generated as a re-

sult of combustion processes, including the burning of fossil fuels for steam generation, heating and household cooking, agricultural field burning, diesel-fueled engine combustion, and various industrial processes. Emissions from these anthropogenic sources tend to be in fine fractions. However, some industrial and other processes that produce large amounts of dust, such as cement manufacturing, mining, stone crushing, and flour milling, tend to generate particles larger than 1 micron and mostly larger than 2.5 microns. In cold and temperate parts of the world, domestic coal burning has been a major contributor to the particulate content of urban air. Traffic-related emissions may make a substantial contribution to the concentration of suspended particulates in areas close to traffic. Some agroindustrial processes and road traffic represent additional anthropogenic sources of mostly coarse particulate emissions.

The largest stationary sources of particulate emissions include fossil-fuel-based thermal power plants, metallurgical processes, and cement manufacturing. The physical and chemical composition of particulate emissions is determined by the nature of pollution sources. Most particles emitted by anthropogenic sources are less than 2.5 microns in diameter and include a larger variety of toxic elements than particles emitted by natural sources. Fossil fuel combustion generates metal and sulfur particulate emissions, depending on the chemical composition of the fuel used. The USEPA (1982b) estimates that more than 90% of fine particulates emitted from stationary combustion sources are combined with sulfur dioxide (SO_2). Sulfates, however, do not necessarily form the largest fraction of fine particulates. In locations such as Bangkok, Chongqing (China), and São Paulo (Brazil), organic carbon compounds account for a larger fraction of fine particulates, reflecting the role of emissions from diesel and two-stroke vehicles or of smoke from burning coal and charcoal. Although sulfates represent a significant share (30–40%) of fine particulates in these cases, care is required before making general assertions about the relationship between sulfates and fine particulates, since the sources and species characteristics of fine particulates may vary significantly across locations. Combustion devices may emit particulates comprised of products of incomplete

combustion (PICs, which may include toxic organics) and toxic metals, which are present in the fuel and in some cases may also be carcinogenic. Particulates emitted by thermal power generation may contain lead, mercury, and other heavy metals. The melting, pouring, and torch-cutting procedures of metallurgy emit metal particulates containing lead, cadmium, and nickel. Particles emitted by the cement industry are largely stone or clay-based particulates that may contain toxic metals such as lead.

Impacts of Exposure

Human Health Effects

The respiratory system is the major route of entry for airborne particulates. The deposition of particulates in different parts of the human respiratory system depends on particle size, shape, density, and individual breathing patterns (mouth or nose breathing). The effect on the human organism is also influenced by the chemical composition of the particles, the duration of exposure, and individual susceptibility. While all particles smaller than 10 microns in diameter can reach the human lungs, the retention rate is largest for the finer particles.

Products of incomplete combustion, which form a significant portion of the fine particulates, may enter deep into the lungs. PICs contribute significantly to health impacts associated with fine particulates.

Clinical, epidemiologic, and toxicological sources are used to estimate the mortality and morbidity effects of short- and long-term exposure to various particulate concentration levels. Several studies have found statistically significant relationships between high short-term ambient particulate concentrations and excess mortality in London and elsewhere. The estimated 4,000 excess deaths in the London metropolitan area in December 1952 were associated with BS measurements equivalent to a 4,000 $\mu\text{g}/\text{m}^3$ maximum daily average ambient concentration of particulates (Schwartz and Dockery 1992b). Schwartz (1993b) has also found a significant association between daily average PM_{10} concentrations and mortality at concentrations below the current U.S. standard of 150 $\mu\text{g}/\text{m}^3$ for short-term PM_{10} concentrations.

Population-based cross-sectional and longitudinal studies (see, for example, Lipfert 1984; Dockery et al. 1993) have found an association between long-term exposure and mortality. Using 14-to-16-year studies in six U.S. cities, and controlling for individual risk factors, including age, sex, smoking, body-mass index, and occupational exposure, Dockery et al. (1993) found a significant connection between particulate air pollution and excess mortality at average annual PM_{10} concentrations as low as 18 $\mu\text{g}/\text{m}^3$, well below the current U.S. ambient standard of 50 $\mu\text{g}/\text{m}^3$. Studies on the effect of particulates on human health summarized by Ostro (1994) suggest an increase in human mortality rates ranging from 0.3% to 1.6% for each 10 $\mu\text{g}/\text{m}^3$ increase in average annual PM_{10} concentrations.

A study conducted on over a half million people in 151 U.S. metropolitan areas during 1982–89 by Pope et al. (1995) found that death rates in the areas most polluted with fine particulates were 17% higher than in the least polluted areas, as a result of a 31% higher rate of death from heart and lung disease, even when most cities complied with the U.S. federal standards for particulate pollution. Cities with average pollution that complied with federal standards still had about a 5% higher death rate than the cleanest cities.

In addition, relationships between morbidity and short- and long-term exposure to particulate matter have been found in a number of studies. Schwartz et al. (1993) found a significant increase in emergency room visits among people under the age of 65 in areas with daily average PM_{10} concentrations that were less than 70% of the U.S. air quality standard of 150 $\mu\text{g}/\text{m}^3$. Several studies carried out in Canada, Germany, Switzerland, and the United States have found an association between respiratory symptoms and exposure to long-term ambient particulate concentrations of about 30–35 $\mu\text{g}/\text{m}^3$, without any evidence of a threshold level below which health effects do not occur. (For a summary, see Schwartz 1991/92.) Kane (1994) demonstrated an association between mineral dusts such as silica or asbestos fibers accumulating in the lungs and a characteristic spectrum of diseases. Recently, the potential carcinogenic effect of certain dust compounds has been analyzed, and in some cases (for example, for silica dust),

limited evidence of carcinogenic effects has been found (see Ulm 1994).

Recent epidemiologic evidence (for example, Schwartz 1991/92; Schwartz and Dockery 1992b; Ostro 1994) suggests that there may be no safe threshold for fine particulate matter and that the effects are linearly related to concentration.

Other Effects

Vegetation exposed to wet and dry deposition of particulates may be injured when particulates are combined with other pollutants. Coarse particles, such as dust, directly deposited on leaf surfaces can reduce gas exchange and photosynthesis, leading to reduced plant growth. Heavy metals that may be present in particulates, when deposited on soil, inhibit the process in soil that makes nutrients available to plants. This, combined with the effects of particulates on leaves, may contribute to reduction of plant growth and yields. In addition, particulates contribute to the soiling and erosion of buildings, materials, and paint, leading to increased cleaning and maintenance costs and to loss of utility.

Particulate emissions have their greatest impact on terrestrial ecosystems in the vicinity of emissions sources. Ecological alterations may be the result of particulate emissions that include toxic elements. Furthermore, the presence of fine particulates may cause light scattering, or atmospheric haze, reducing visibility and adversely affecting transport safety, property values, and aesthetics.

Ambient Standards and Guidelines

The most frequently used reference guidelines for ambient particulate concentration are those of WHO, the EU, and the USEPA. These guidelines are based on clinical, toxicological, and epidemiologic evidence and were established by determining the concentrations with the lowest observed adverse effect (implicitly accepting the notion that a lower threshold exists under which no adverse human health effects can be detected), adjusted by an arbitrary margin of safety factor to allow for uncertainties in extrapolation from animals to humans and from small groups of humans to larger populations.¹ The WHO guidelines are based on health considerations alone;

the EU and USEPA standards also reflect the technological feasibility of meeting the standards. In the EU, a prolonged consultation and legislative decisionmaking process took into account the environmental conditions and the economic and social development of the various regions and countries and acknowledged a phased approach to compliance. A potential tradeoff was also recognized in the guidelines for the combined effects of sulfur dioxide and particulate matter (see European Community 1992).

Conclusions

The main objective of air quality guidelines and standards is the protection of human health. Since fine particulates (PM₁₀) are more likely to cause adverse health effects than coarse particulates, guidelines and standards referring to fine particulate concentrations are preferred to those referring to TSP, which includes coarse particulate concentrations.

Scientific studies provide ample evidence of the relationship between exposure to short-term and long-term ambient particulate concentrations and human mortality and morbidity effects. However, the dose-response mechanism is not yet fully understood. Furthermore, according to WHO (1987), there is no safe threshold level below which health damage does not occur. Therefore, policymakers may have to consider acceptable risk rather than try to achieve absolute safety when setting ambient particulate concentration standards. Furthermore, ambient guidelines can become an effective part of the environmental management system only if implementation is feasible and the enforcement of other policy instruments ensures their attainment. Consideration should therefore be given to the technical feasibility and the costs of attainment.

Another difficulty is that airborne particulates are rarely homogeneous: They vary greatly in size and shape, and their chemical composition is determined by factors specific to the source and location of the emissions. The combined effects and interactions of various substances mixed with particulates have not yet been established (except for sulfur dioxide), but they are believed to be significant, especially where long-term exposure occurs. Measurement techniques and their

reliability may vary across regions and countries, and so may other factors, such as diet, lifestyle, and physical fitness, that influence the human health effects of exposure to particulates.

Recommendations

In the long term, countries should seek to ensure that ambient exposure to particulates, especially to PM_{10} , do not exceed the WHO recommended guidelines (see Table 1). In the interim, countries should set ambient standards for total particulates, PM_{10} , or both that take into account (a) the benefits to human health of reducing exposure to particulates; (b) the concentration levels achievable by pollution prevention and control measures; and (c) the costs involved in meeting the standards. In adopting new ambient air quality standards, countries should set appropriate phase-in periods during which districts or municipalities that do not meet the new standards are expected to come into compliance and will be assisted to attain the standards. Where there are large differences between the costs and benefits of meeting air quality standards, it may be

appropriate to establish area-specific ambient standards case by case.

Prior to carrying out an environmental assessment, a trigger value for annual average concentrations of PM_{10} should be agreed on by the country and the World Bank. Countries may wish to adopt EU, USEPA, or WHO guidelines or standards as their trigger values. The trigger value should be equal to or lower than the country's ambient standard. The trigger value is not an ambient air quality standard but simply a threshold. If, as a result of the project, the trigger value is predicted to be exceeded in the area affected by the project, the EA assessment should seek mitigation alternatives on a regional or sectoral basis. In the absence of an agreed value, the World Bank Group will classify an airshed as moderately degraded if the annual average concentration levels of particulates are above $50 \mu\text{g}/\text{m}^3$ or if the 98th percentile of 24-hour mean values over a one-year period is estimated to exceed $150 \mu\text{g}/\text{m}^3$ of PM_{10} . In areas where PM_{10} measurements do not exist, the value of $80 \mu\text{g}/\text{m}^3$ for TSP will be used. Airsheds will be classified as having poor air quality with respect to particulate mat-

Table 1. Reference Standards and Guidelines for Average Ambient Particulate Concentration
(micrograms per cubic meter)

Standard or guideline	Long-term (annual)			Short-term (24 hours)		
	PM_{10}	BS	TSP	PM_{10}	BS	TSP
EU limit values		80 ^a	150 ^b		250 ^c	300 ^d
EU guide values		40–60 ^a			100–150 ^e	
USEPA primary and secondary standards	50 ^f			150 ^g		
WHO guidelines ^h		40–60	60–90		100–150	150–230
WHO guidelines for Europe ^g	50		70 ⁱ	125	120	

Notes: PM_{10} , particulate matter less than 10 microns in aerodynamic diameter; BS, black smoke (converted to $\mu\text{g}/\text{m}^3$ measure); TSP, total suspended particulates.

a. Median of daily mean values.

b. Arithmetic mean of daily mean values.

c. 98th percentile of all daily mean values throughout the year.

d. 95th percentile of all daily mean values throughout the year.

e. Daily mean values.

f. Arithmetic mean.

g. Guideline values for combined exposure to sulfur dioxide and particulates.

h. Not to be exceeded for more than one day per year.

i. Guideline for thoracic particles. According to International Organization for Standardization standard ISO-TP, thoracic particle measurements are roughly equivalent to the sampling characteristics for particulate matter with a 50% cutoff point at 10 microns diameter. Values are to be regarded as tentative at this time, being based on a single study that also involved sulfur dioxide exposure.

Sources: European Community 1992 (EU); United States, CFR (USEPA); WHO 1979 (WHO guidelines); WHO 1987 (WHO guidelines for Europe).

ter if the annual mean value of PM_{10} is greater than $100 \mu\text{g}/\text{m}^3$ or if the 95th percentile of 24-hour mean values of PM_{10} over a period of one year is estimated to exceed $150 \mu\text{g}/\text{m}^3$.

Good practice in airshed management should encompass the establishment of an emergency response plan during industrial plant operation. It is recommended that this plan be put into effect when levels of air pollution exceed one or more of the emergency trigger values (determined for short-term concentrations of sulfur dioxide, nitrogen oxides, particulates, and ozone). The recommended emergency trigger value for PM_{10} is $150 \mu\text{g}/\text{m}^3$ for 24-hour average concentrations. Where PM_{10} measurements do not exist, the value of $300 \mu\text{g}/\text{m}^3$ for TSP is recommended.

Note

1. Adverse effect is defined as "any effect resulting in functional impairment and/or pathological lesions that may affect the performance of the whole organism or which contributed to a reduced ability to respond to an additional challenge" (see USEPA 1980).

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